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ABSTRACT

Title of Thesis: CREATIVE DESIGN METHODS AND INVESTIGATION OF CELLULOSE FIBER TRANSPORT AND APPLICATION SYSTEM

Degree Candidate: Mack-Jan Honoré Spencer

Degree and Year: Master of Science, 1998

Thesis directed by: Professor Kenneth Kiger
Professor Linda Schmidt
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Many difficult design problems require the development of creative design solutions to achieve feasible results. Designers and engineers have searched for methods to enhance creativity in problem-solving to acquire new ideas. A creative design method is a process by which new, independent ideas are generated using knowledge to solve some problem or achieve an objective. Four prominent creative design methods were investigated to explore the extent to which they actually enable creativity by applying them to the design of a novel cellulose application system. Correlations between the four design methods were also discovered. These investigated methods were analogical reasoning, brainstorming, synectics, and the theory of inventive problem solving (TIPS).

In support of the cellulose application system design, a scientific investigation examining the pneumatic suspension and transport of cellulose fibers was conducted. Measurements of air pressure gradients were conducted for various cellulose mass fractions to investigate the pressure drops involved in air-cellulose flow in pipes. Additionally, mixture dispersions were examined using laser testing to analyze the physical properties of air-cellulose mixtures in transport. Moody diagrams and pressure gradient curves were developed and compared to the physical dispersion characteristics of the air-cellulose mixtures.

CREATIVE DESIGN METHODS AND INVESTIGATION OF CELLULOSE FIBER TRANSPORT AND APPLICATION SYSTEM

By

Mack-Jan Honoré Spencer

Thesis submitted to the Faculty of the Graduate School of the
University of Maryland, College Park in partial fulfillment
of the requirements for the degree of
Master of Science
1998

Advisory Committee:

Professor Linda Schmidt, Chair
Professor Kenneth Kiger
Professor James Wallace

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Finally, I want to thank my family for giving me so much support and encouragement when I didn't think I could make it. Dream Big!

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LIST OF ABBREVIATIONS

Re	-	Reynolds number
V	-	average flow velocity
d	-	inner pipe diameter
ν	-	kinematic viscosity
f	-	friction factor
ε	-	pipe roughness
h_f	-	head loss
L	-	pipe length
g	-	acceleration due to gravity
ΔP	-	change in pressure
ρ	-	density
Q	-	flow rate
inH_2O	-	inches of water
$\dot{m}$	-	mass flow rate

Chapter 1: Introduction

This thesis involved the investigation of numerous creative design methods. It also involved the investigation of the pneumatic suspension and transport of cellulose fibers in air. The basis of these investigations was a design problem presently being faced by the cellulose insulation industry.

1.1 Problem Description

Cellulose insulation is extensively used for insulation in buildings and houses. This insulation is generally made up of finely cut paper pieces which vary in size. Mixed with small amounts of other substances to make them fire and corrosion resistant, these paper pieces have an interlocking nature which allow them to cling together. When the cellulose pieces are made wet, they stick together much more strongly and with some impact force can adhere to other surfaces. This is similar to wetting a wadded piece of paper so that it may stick to something more effectively.

To serve as the insulation for walls in a building, the cellulose must be forced into a wall cavity and stay there intact throughout the building's lifetime. Presently to accomplish this, varying masses of cellulose are propelled with air through a 3"- 4" tube and blown forcefully onto the wall through a widened nozzle. Upon exiting the nozzle, a fine mist of water wets the cellulose to make it stickier. Figure 1 shows the present process of blowing the cellulose against the wall. Once it impacts the wall, some

cellulose sticks in the wall cavity and other cellulose bounces off or is blown off by the air, and falls to the ground. Later, the cellulose on the ground is picked up and put into a storage hopper so it can be reapplied. Because the surface of the packed cellulose is not smooth, a scrubber brush must be used to smooth out the surface in relation to the wall studs. Figure 2 shows the process of "scrubbing" the wall to smooth the packed cellulose surface.

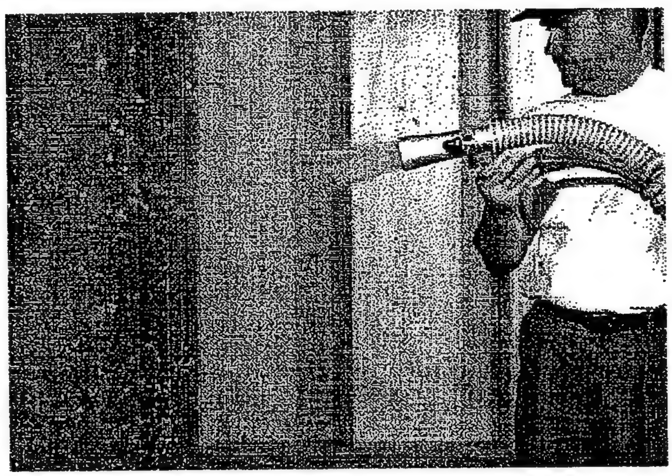


Figure 1: Photograph of Cellulose Application Process [Krendl]

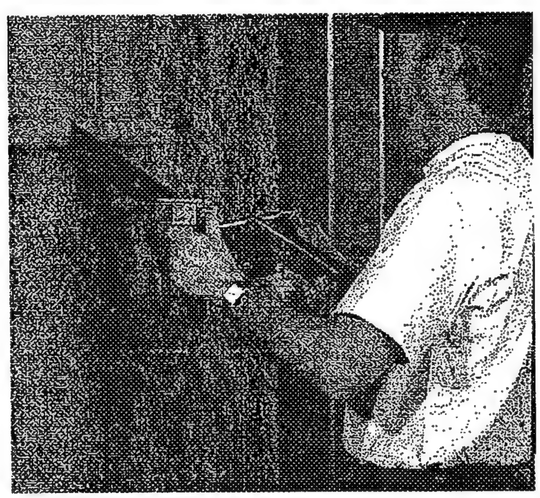


Figure 2: Photograph of Cellulose Scrubbing Process [Krendl]

The cellulose industry is seeking a new method of cellulose insulation application that minimizes the amount of cellulose that fails to be applied to the wall, eliminating many man-hours needed to constantly pick up and reapply this cellulose. Most of the cellulose that falls onto the ground is blown off of the wall due to the excess amount of air coming out with the cellulose. An optimum application method would apply the cellulose to the wall cavity with no cellulose falling to the ground and without the use a of a separate scrubber. This method would continue to meet all the necessary standards the cellulose insulation industry has in regards to cellulose wetness, firmness, resistance to sag, and other similar factors.

1.2 Research Issues

Both the creative design investigation and cellulose pneumatic transport investigation discussed in this thesis were based on this design problem. Four creative design methods were used to help develop practical and innovative solutions to the present cellulose design problem. These methods were investigated to explore the extent to which they actually enabled creativity in design.

Due to the difficulty of the design problem, more information was needed regarding air-cellulose flow to develop a feasible design. The pneumatic transport investigation was accomplished to help provide more valuable scientific information regarding the process of multi-phase flow and the transport of varying sizes of

interlocking cellulose fibers at different air flow rates. This information could be used in the future to help both designers and scientists working with two-phase flow.

1.3 Organization

In this thesis report, creative design methods will first be discussed and investigated in regards to the design problem. Then, the investigation of cellulose transport will be discussed. Chapter 2 presents a description of creative design and associative thinking while Chapter 3 presents an analysis of four creative design methods. Chapter 4 discusses the key relationships that the investigated methods have with one another and the contribution of this research to the design community. Chapter 5 presents a significant problem that we faced in design leading to the need to scientifically investigate cellulose pipe flow. Chapter 6 provides the characteristics of air-cellulose flow while Chapter 7 describes the experimental set-up. Chapter 8 presents the results and a discussion of the experiments.

Chapter 2: Creative Design and Associative Thinking

This chapter presents a description of the concept of creativity and key factors that affect the "level" of creativity for a particular idea. Additionally, the view of knowledge as a pool of associated ideas is discussed along with how creative acts affect the knowledge pool. A method of recording this process called mind mapping is presented and will be used as a basis for tracking the creative process in the investigated creative design methods.

2.1 Creativity in the Design Process

For ages, humans have had little understanding of the concept of creativity. Some view creativity as a natural genetic trait that allows some people to develop spontaneous ideas with little effort. Others believe creativity is a learned skill developed through rigorous application of creative abilities. Still others believe that creativity is a brilliant human ability that we could never understand. With all of these perceptions of what creativity is and what it takes for something to be creative, it is very difficult to pinpoint a precise meaning for the term. Whatever the belief, most agree that creativity is some ability that sentient beings have allowing them to produce new ideas or concepts.

By definition, the term "creativity" basically means an ability to create or bring into being. In design, creativity more specifically implies an ability to be original and imaginative [American Heritage Dictionary 1990]. In design, people generate ideas to

solve a particular problem. These ideas are always generated from some pool of knowledge, whether it be one person's individual knowledge, a group's combined knowledge, or knowledge gained from outside sources like computers. "Creative" ideas are thoughts that tend to be original or imaginative.

Many people view creativity rather differently. Some people believe that creativity is some genius skill few people are blessed with, like Edison, Einstein, or the Wright brothers. However, this is a false belief since anyone can hone his or her creative abilities through consistent use and practice. In history, many people who were not generally thought to be "creative" have applied their innate abilities to think of new ideas and have developed scores of new processes and inventions. Some have defined creativity as the "combining of seemingly disparate parts into a functioning and useful whole" [Kalley 1996]. Others define it simply as "coming up with something new" [Kalley 1996]. A more specific definition states that the creative process is "a mental process in which past experience is combined and recombined to form a new combination which will satisfy some need" [Kalley 1996].

Creativity can be investigated from a product standpoint as well as a process standpoint. Studying creativity from the standpoint of the product would entail defining what makes an artifact or thing creative. As will be discussed later in this section, the creativity of an artifact is determined by the ideas and knowledge that are present in the specific environment it exists in. Since creativity is based on a foundation of knowledge and the generation of ideas, this paper will investigate the "process" by which these creative ideas are made rather than the product itself, since that depends on the environment.

2.2 The Creative Process

Most people would agree that a creative process is a mental process that begins in some basis of knowledge. A creative process occurs when something new and original is conceived. According to the dictionary, originality implies an "ability to think or express oneself in an independent and individual manner; freshness or novelty" [*Random House*]. Originality is synonymous to inventiveness and ingenuity. In any case, creativity seems to involve a mental process by which a new, independent idea is conceived using knowledge.

A key aspect in creativity is where a creative process actually occurs. It can be reasoned that the only necessary trait needed for a thing to be creative is an ability to take in or hold information, link it to some other piece of information (interpret a meaning or significance), and be able to rearrange and add links at will. The linking of information to one another allows the information to have meaning; otherwise it is only raw data. For example, the term "ssarg" (in English) has no meaning by itself. But when it is defined or perceived as a plant, a food, green, growing from ground, etc., it gains meaning. It becomes associated to other concepts. Even further, "ssarg" can be reversed to state "grass." Now, the term has meaning since it can be associated with various thoughts from an English speaking standpoint. Knowledge is information that is interpreted a certain way by linking it to other information. If something can hold information and link it to other information, it has knowledge. If something has the ability to change, rearrange, or add links within this knowledge (i.e. change or add meaning to

information), it can create new knowledge and new ideas, and therefore can be creative. In this respect, anything that has knowledge and can change the links or significance of that knowledge has the ability to be creative.

Creating a new link in one's mind is the essence of creativity. On the most basic level, creating a new significance or relevance to some piece of information can be a creative act. A creative act basically occurs within a pool of knowledge when two or more originally dissimilar ideas are linked together. Roger Cardinal states, "Everything is consistent in the analogical vision: each thing connects with each other thing, and all things cohere in a global motion which is creativity" [Roukes 1988].

2.3 Idea Independence in Creativity

Many would argue that just thinking of some new idea is not really creative. Another source, such as another person, could "give" a new idea to you, but that would not seem creative even though new ideas are being linked together. The level of **independence** or dissimilarity that the information had before being linked plays a key role in determining how creative a new idea is. There are abstract "levels" of creativity based on the particular independence that the original information has. The **environment** in which a new idea is made plays an important role in determining this independence and usually determines how creative an idea is.

In the 1400s, Leonardo da Vinci made up sketches and models for an "ornithopter," which was a flying machine kept aloft and propelled by flapping wings.

This device had similar movements to that of a bird, but it was to be powered and flown by human muscle power. He produced the idea from seeing birds flying and trying to mimic such movements so that a human could fly [*Horizons* 1985]. Presently, hang gliders have many of the same characteristics that the ornithopter had, without flapping wings.

The particular environment in which the idea is introduced will usually determine how creative it is. In Leonardo da Vinci's world, the ornithopter was considered a very creative idea. No one had flown before and linking human beings and flying birds was thought to be ludicrous at the time. In the environment of his time, he independently came up with this idea based on his observation and by creating his own unique mental links. However, if someone today comes up with a fairly typical hang glider design based on what he or she has seen in other hang glider designs, it will not be considered very creative since this design idea is not very independent of other ideas already in the environment.

Consider a second example. If a woman living in the jungles of South America today sees a bird fly and then creates a model of a flying glider, yet had never seen modern civilization or a flying machine, that could still be considered a creative act based on the environment she was in and the dissimilarity of the ideas that she had to bring together. People in our world might not see that design as creative because of our more modern environment, but from the perspective of the primitive jungle culture, such a design is very creative. There is no real black and white scale to measure if an idea is creative or not, since the point of reference is really the key to judging its creativity.

2.4 Thinking by Linking or Association

We have not yet discovered a definitive way by which humans produce ideas. However, humans and most organisms have been found to think by "association" [Robbins 1996]. The association of ideas is "the phenomenon by which imagination gears itself to memory and causes one thought to lead to another" [Osborn 1957]. In one short moment, one thought can lead to a number of other thoughts that are linked in some way to one another.

Human beings and most other beings think consistently by association: linking or connecting one piece of knowledge to another piece of knowledge. For example, if someone asks you what you think about "horror movies," you will instantly search in your mind for everything you have known or experienced with regards to horror movies. Such profound images as blood, death, gore, screaming, thrills, madness, and anger would most likely be accessed. Mental pictures of movies watched, sounds heard, various emotions experienced, and other memories will instantly be tapped. Your mind will find all associations it has with horror and movies and tap into that knowledge to answer the question. Figure 3 is a conceptual view, in words, of some ideas the mind might generate if it focused on "horror movies." These words represent some type of visual images or experiences. These images and experiences are thoughts that we may "associate" with horror movies.

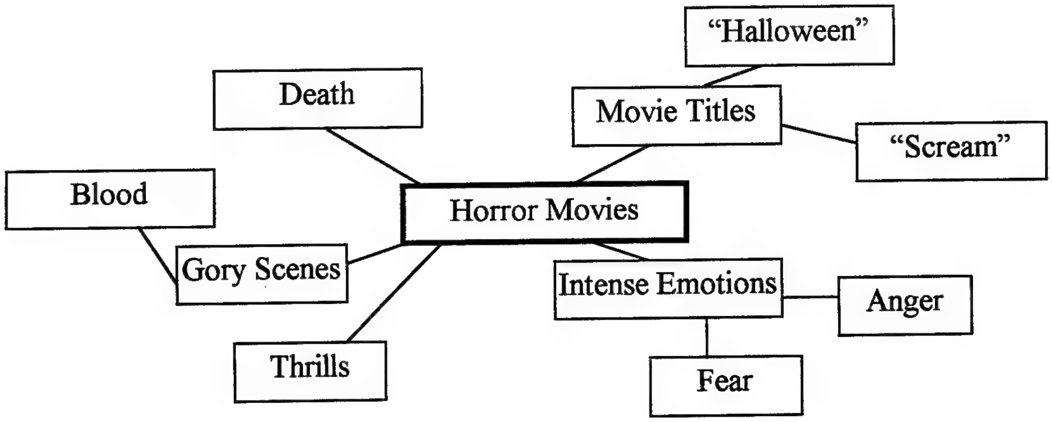


Figure 3: "Horror Movies" Association of Ideas

Information is stored in our minds through associations to other pieces of information. This collection of information and the interpretation of that information is knowledge. Every experience or piece of data is accessed based on its relation to other data. A person can recall this data by consciously or subconsciously asking a specific question and tapping all available information linked to the topics of this question. Based on the questions we ask ourselves or the specific information we "search" for, we can recall certain stored experiences and knowledge through their association [Robbins 1996].

2.5 The Knowledge Pool

To better understand the concept of knowledge and associative thinking, imagine that your personal knowledge is an ever-changing and adapting body of material from the

vast realm of all information in the universe. As you learn, you perceive or take in new pieces of information which add to this three-dimensional body of knowledge. The center of this body is the foundation or core of most of your knowledge. The core would include knowledge you would use most like words, numbers, colors, or an abundance of other consistently applied thoughts. Knowledge within this core would tend to be so engrained that a person would "know" it subconsciously and would need almost no conscious effort to access it. Legs or extensions would sprout out of this body representing specific domains of knowledge which are only somewhat related to other portions of knowledge and therefore less familiar to a person. Figure 4 represents a two-dimensional (2-D) view of this body of knowledge in the form of a **knowledge pool**.

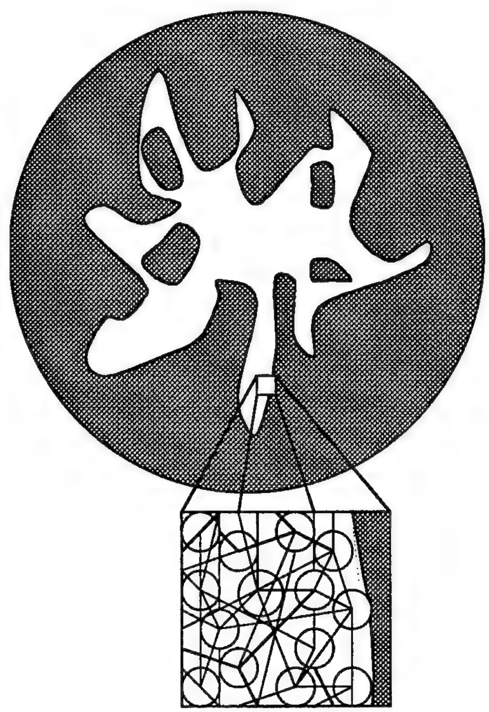


Figure 4: Visual Representation of a Knowledge Pool

The knowledge pool represents a two-dimensional cross section of the chain of associated information that makes up a person's knowledge. This pool can expand in all directions. Holes theoretically represent unknown portions of information which are not linked into our knowledge pool. In the center of the pool one finds the core foundation of knowledge, which would have links to all kinds of other experiences. The thin extensions or legs in Figure 4 represent a specialized domain of knowledge. A person would have a small understanding of knowledge in these legs and this information would tend to have fewer relationships to other knowledge. A good example would be a difficult college math class in which a person understood some of the basic concepts but did not relate much of the class to other domains of knowledge.

The blown-up portion in Figure 4 shows individual knowledge segments and how they would link to numerous other segments of knowledge. Each circle represents one minute segment or piece of knowledge. Each segment holds some piece of information regarding an experience, observation, thought, or other mental record. The lines show links between these knowledge segments. These links represent some connection a piece of knowledge has with another piece of knowledge. The links could be some connection in functions, physical properties, actions, or other associations that segments have with one another. Some links could be much stronger than others based on how much they are focused on. Many times, segments will have a dependent association on other knowledge segments. For example, one would need to understand numbers before one could understand addition. This knowledge pool model is not a perfect representation of information storage in the brain, but it helps to understand how the mind stores and accesses information through linking.

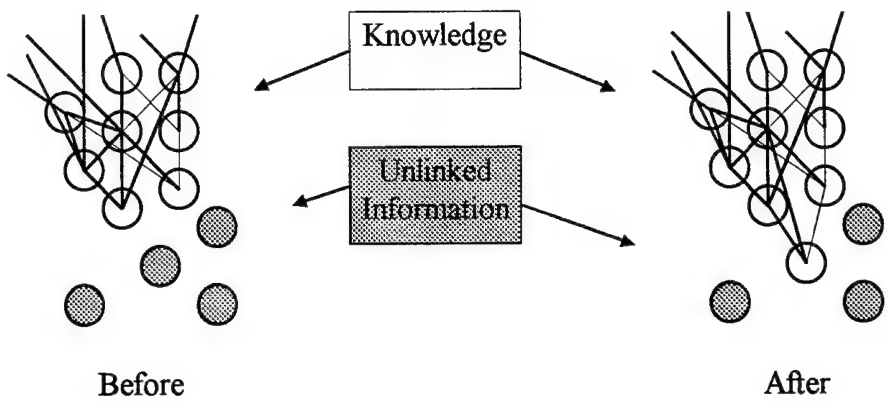


Figure 5: Linking of Information to Knowledge Pool

Figure 5 is a visual example of how a new piece of outside information would become a part of the knowledge pool through linking. The key point is that through linking, otherwise random information becomes knowledge. By being linked to other segments of knowledge, the information can be interpreted and perceived based on relations to other knowledge. The information gains meaning and relevance. In that respect, all organisms look at situations in different ways because of their varied perceptions of the information presented. Two people might smell a pizza and one begins to get sick while the other starts to salivate. The first person had a prior experience in which she ate too much pizza and now hates it so she becomes sick when she sees or smells it. However, the other person has only had it once before and loves it intensely. Both people receive the same information but perceive it differently because of the different links and associations they've created.

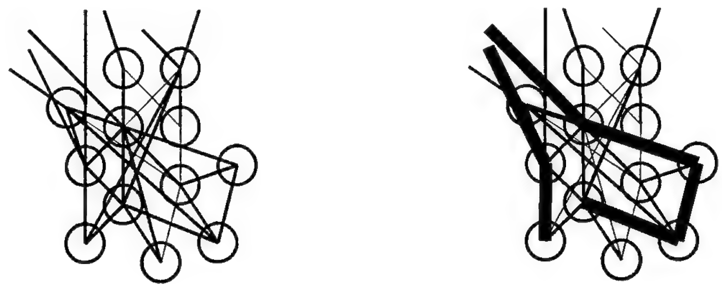


Figure 6: Strengthening and Weakening of Links Through Use

Figure 6 shows how the strength of various links can change so that certain pieces of knowledge are more easily accessed, while other links become weaker since they are not used often. This is comparable to a highly used super highway versus a barren dirt road. One is constantly used and maintained (validated) while the other is used little and rarely maintained.

For example, if you are consistently or intensely told that you are a "winner" and you focus strongly on that perception, you will take in information and recall experiences to validate that focus. You will look for things around you and remember past activities that validate the perception that you are a winner. Since the conscious mind can only focus on a few things at a time, other information that might conflict with that perception will most likely be ignored. With consistent and/or intense focus, this "winner" perception will become the truth for you since that is all you have perceived. This "enlightenment" occurs through constantly analyzing a body of knowledge and comparing it to the surrounding environment. In the human mind, links and ideas that are not validated by information from the environment will begin to be ignored and forgotten,

like a barren, unmaintained dirt road. The links and ideas that are continually or intensely validated by the environment will be strong and routinely accessed, like a well-maintained super highway. The information that is consistently focused on in the environment will become perceived as truth to the mind.

2.6 Creativity in the Knowledge Pool

As was discussed earlier, the highest levels of creativity occur when very dissimilar ideas are brought together independent of some other source and form new meanings or significance. Creativity is lower when the ideas are not as dissimilar or disassociated within the pool of knowledge that the information comes from. For that reason, people who tend to look at many different ideas from all realms will also tend to have more creative ideas since they are bringing together very dissimilar ideas. A creative idea can come about two ways:

1. By suddenly developing a new link between ideas even though there was no new information given.
2. By discovering or observing something completely new and by creating links to this new information.

Sometimes a creative idea comes about just because someone looked at a problem from a different angle yet already had all the needed information. Through association, one can

solve a problem with what one already knows. Other times, new information must be discovered or experienced to produce creative ideas.

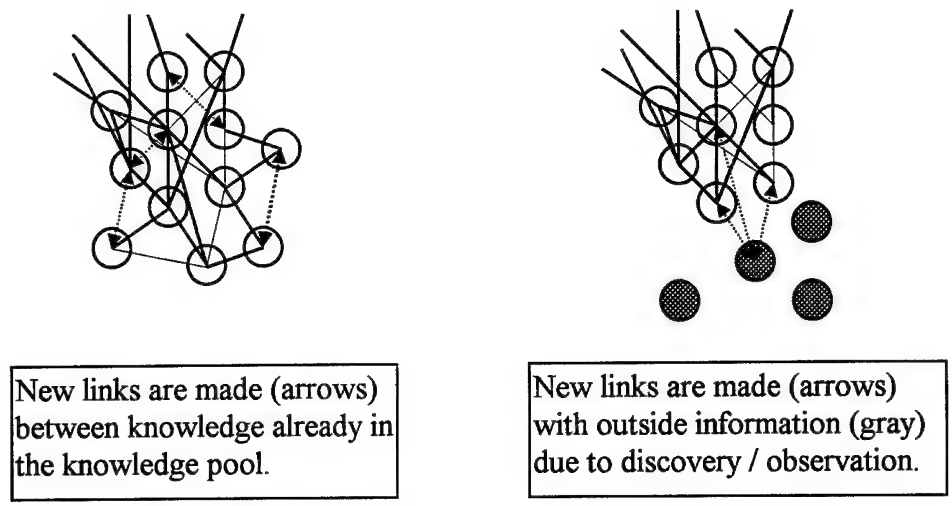


Figure 7: Two Ways a Creative Act Occurs in a Knowledge Pool

Figure 7 visually displays the two ways that a creative act occurs in a knowledge pool. In both cases, a new link is created in the knowledge pool. In the first case, that link is made internally within the knowledge pool with no new outside information involved. In the other case, new information is perceived using the senses and linked to pieces of knowledge in the knowledge pool. This process of making new links is the foundation of creativity.

2.7 Use of Mind Mapping to Record Creative Process

One key technique, known as mind mapping, will be used extensively during the investigation of the creative design methods used in this thesis. Mental mapping has been hailed as a technique to enhance creativity in problem solving and aid in understanding situations in general [Buzan 1993]. It is based on the concept of creating visual analogies between elements since the human mind tends to think in pictures. Tony Buzan, the chief developer of the process of mental mapping, states that "mind maps are a way of representing associated thoughts with symbols rather than with extraneous words something like organic chemistry" [Buzan 1993]. A mind map tracks the associated thoughts that one has with respect to a specific central thought or question. In essence, a mind map is a visual diagram of a knowledge pool and the chain of linked ideas.

Since people tend to think in pictures, associated thoughts can be recorded as pictures with word explanations. A mind map can be infinite in length and take on just about any structure, since it is based on associations. A person can basically associate a thought with a central thought, next make another association to that thought, and continue to do that over and over. Since everything can be associated to something else in one way or another, a mind map can go on forever with infinite width and depth.

To create mind maps, one begins with a central thought and branches out in all directions to produce a growing, organized structure of words and images. Mind maps will generally begin to take on the structure of memory itself and show links between various associated ideas. They can help to organize and understand information or to

generate new ideas. Design naturally contains a idea generation stage in which new ideas are produced that might solve a problem. Many times, brainstorming sessions are used to generate these ideas. Mental mapping is a technique to "map" out the associated thought process during idea generation [Buzan 1993]. Figure 8 is an example of a textually based mind map which does not contain pictures. This shows various ideas associated in a map-like structure for being on a farm in 1950. The process of mind mapping will used in later sections to describe various ideas in regards to the creative design methods presented.

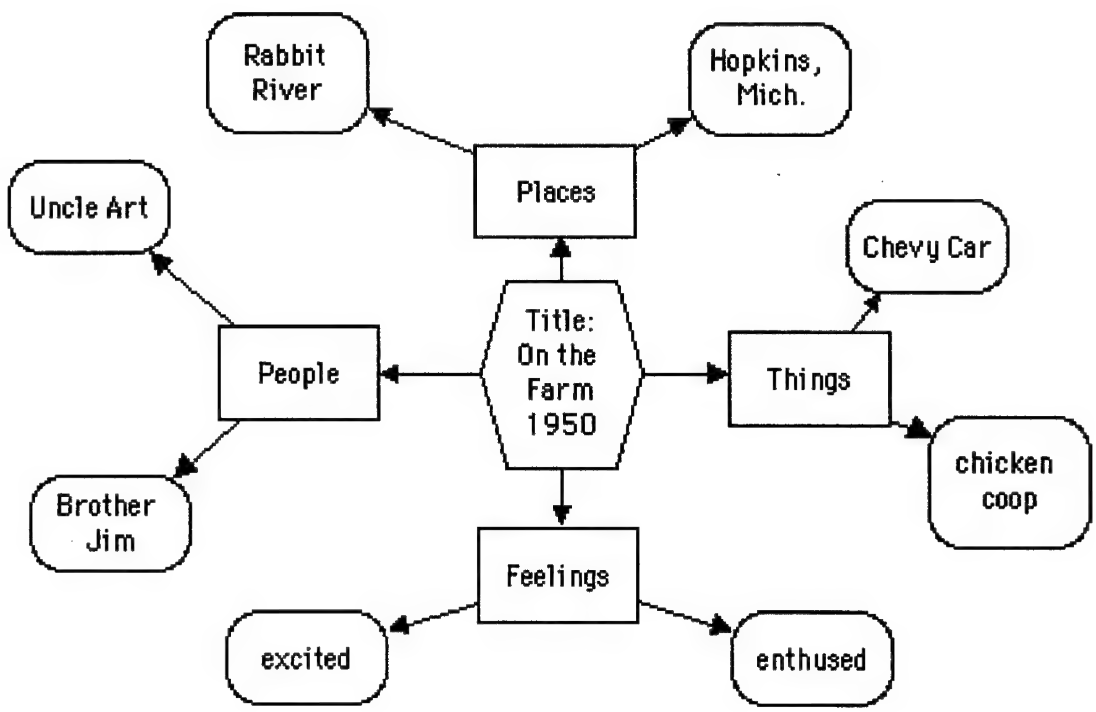


Figure 8: Textual Mind Map [*Mind Maps* 1998]

Chapter 3: Creative Design Methods

In our constantly changing world, so much new information is discovered on a daily basis that it has become difficult to make sense of it all. The ability to look at various technologies or processes and creatively apply them to a practical field has never had higher demand. In recent decades, a great deal of effort has been put forth to find creative design methods and find ways to help humans hone their creative abilities. Numerous processes, methods, and techniques have been investigated and applied in an attempt to create a better understanding of creativity and make it applicable in everyday problem solving. Some of these operations will be investigated for their applicability to creativity and be applied to the cellulose application design problem. The methods that will be investigated include analogical reasoning, brainstorming, synectics, and the theory of inventive problem solving.

3.1 Analogical Reasoning

Analogical reasoning, with mind mapping as a tool, models the associative process within the mind and allows a designer to record this process on paper. It is based totally on associative thinking, which was discussed earlier as the foundation of creativity. Creative ideas can emerge by using this design method to make new links between ideas.

Humans create knowledge and learn by building on associations. The process of "learning" is basically the process of creating new links or associations between pieces of information [Robbins 1996]. This could occur either by taking in new information and linking it to knowledge in the mind, or just by linking knowledge already in the mind in a new way. This can also be described as analogical thinking. Thinking by association is synonymous to making use of mental analogies.

Analogical thinking is the basic foundation by which human beings think. From the day a person is born, information is processed in the mind into knowledge. Links are made between what has already been experienced and *new* information. A baby makes quick associations between crying and getting what it wants (milk, food, attention, etc.) Any person, whether 1 year old or 100 years old, understands *new* information through relating it to what he or she already knows and turning it into knowledge. For example, if I knew nothing about atoms but understood basically how the sun and planets work, I could make associations or analogies between their similar traits based on what I already know about revolving, spinning, size proportions, attractions, etc. I could make almost infinite analogies based on the experiences I've had. I could relate "revolving" to spinning a ball on a string or to spinning a top. I could relate "attraction" to how magnets stick or to static cling.

As we learn more, we build on the associations we have made before. That is why we learn basic speech, math, and reading first when we are very young. For most people, what we learn at young ages becomes the core foundation of our knowledge. As we continue using certain knowledge repetitively, it becomes more engrained and has links to numerous other ideas. For example, you have developed knowledge of reading

this sentence by connecting all you know about letters to make words and then linking those words to meanings or pictures. Together, these meanings and pictures come together as a sentence or paragraph to form an understanding in your mind. Letters and numbers have become a very engrained part of our knowledge through constant daily use.

3.1.1 Creativity through Analogy

Analogical reasoning is the core of creativity within the human mind. Linking information involves recognizing relationships or creating analogies between different concepts. Analogies represent *how* a specific idea is similar or "associated" to another idea. A simple analogy is that a pencil is like a knife. A pencil can be like a knife in that they are both sharp or that they could both be used to stab something. They can also be similar in that they can be held easily in the hand. A pencil and a knife can be similar in a number of different ways, depending on what traits are compared, such as shape, weight, use, color, etc. An experience can also have analogies. For example, that drive in a car was like a roller coaster ride. In this respect, the car drive had similar characteristics to a roller coaster ride: fast, wild, jolting, exciting, scary, etc. In trying to understand a new concept, humans use previous knowledge to try to understand concepts that are not clear or have not been experienced before.

Various theorists have developed approaches to how analogies are used in the human psyche to create understanding of different concepts and develop solutions to problems based on other domains or fields of knowledge. Two of the most widely known theories are Gentner's Structure-Mapping Theory and Holyoaks's Pragmatic Approach which both use analogical thinking as a basis for problem solving. In both theories, a problem is solved through linking various objects, attributes, and relations of one known concept to other concepts [Osborn 1957].

An excellent example of this comes from creating an understanding of an atom's nucleus and electrons based on knowledge of the sun and its planets (Figure 9). Understanding can be created by describing what objects, attributes, and relations are the same in both instances. The electrons and the planets are smaller and attracted to the nucleus and sun, respectively. They have similar traits of size, revolution, and attraction [Keane 1988].

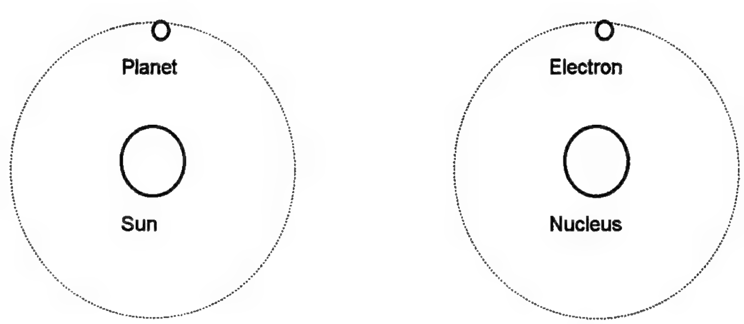


Figure 9: Analogy between Solar System and Atom

The analogical process can play a critical role in two broad types of situations. In both cases, comprehension of some target situation which is not completely understood is

attempted [Keane 1988]. **Unstructured situations** are unfamiliar situations in which one must "borrow" knowledge from known domains of knowledge to understand a new concept and/or create some conceptual understanding of a targeted situation. **Incomplete situations** are relatively familiar situations which can be understood, but the information about them is incomplete. More knowledge must be made of a target domain by using what is known in another domain. Unstructured and incomplete situations differ in that unstructured situations reflect circumstances in which the domain of knowledge involved is unfamiliar or unknown. Therefore, knowledge from some other domain with similarities to this unfamiliar domain is tapped in order to understand the situation. In incomplete situations, the domain of knowledge involved is relatively familiar but there are gaps in information. To create a better understanding, knowledge from other domains is used to fill the gaps [Keane 1988].

3.1.2 Mind Mapping as Applied to the Understanding of Cellulose Application System

At the beginning of this project I had little understanding of the application of cellulose to a wall. This would be considered an unstructured situation since the entire concept was unfamiliar to me. I did not have all the knowledge necessary to form a picture in my mind since I had never experienced applying cellulose to walls. I was not even sure what cellulose was. I had no real pictures to look at, but had to develop understanding based on some things I was told by my instructors and using my own prior knowledge. I knew that some device existed for applying cellulose material to a wall, but

I had to develop a picture of this device without seeing it. Figure 10 is a very generalized mental map of how I analogically understood the current cellulose application device without ever seeing it. While many concepts had more than one analogy to help describe the concept, I used just one for the sake of simplicity.

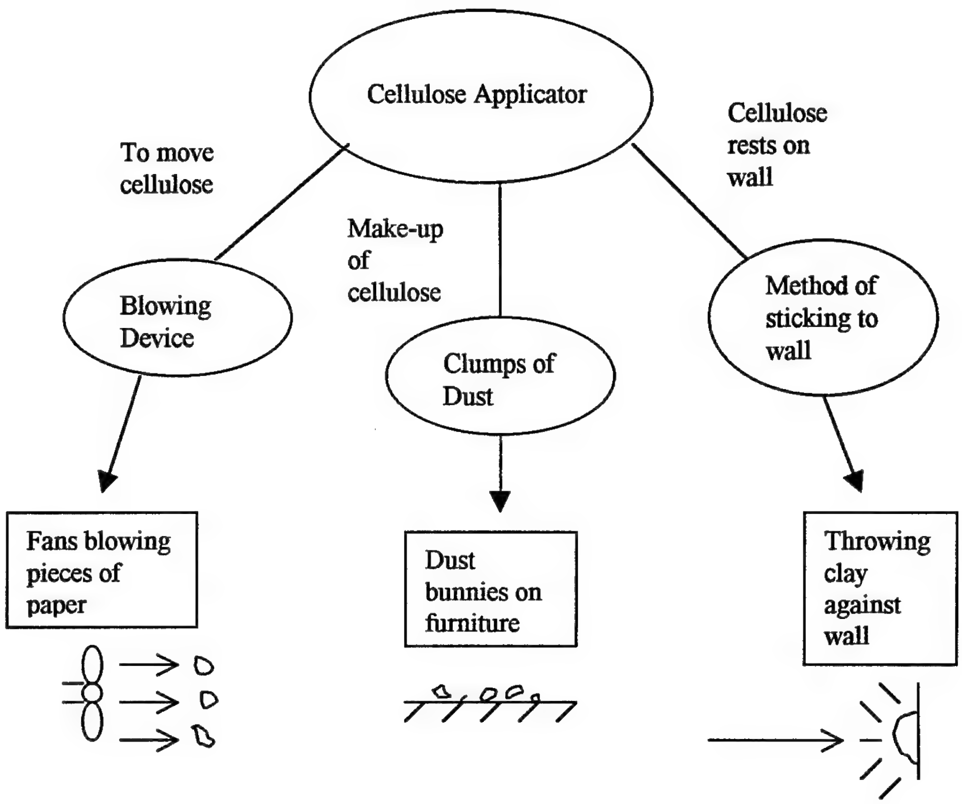


Figure 10: Original Mental Map of Unseen Cellulose Applicator

As can be seen in Figure 10, a mental map includes components that are both objects and actions. Since the mind can recall a concept as physical objects as well as dynamic actions, the mental picture can have a mixture of objects and actions. Words are used to describe the thoughts and pictures. In actuality, this mental picture was based on

innumerable experiences in my past, but the main pictures that stood out in my mind are documented in the map.

I mentally split the system into three components: some blowing device, the cellulose, and a method to stick the cellulose to a wall. I made quick analogies about each of the components based on my own knowledge. This map is a visual representation of this part of my knowledge pool in regards to the cellulose application device. Since I did not know a great deal about this device I had to use other domains of knowledge to create a better understanding.

3.1.3 Validation of Perception of Cellulose Application System

Once I had observed the actual device and was able to work with it, I was able to generate a more complex and slightly different mental map of the cellulose device. As I gained more experience with working on the project, the map became more complex and intertwined as more analogies were developed. I was able to validate my knowledge and refine my perception by observing the device in action. Links that reflected the information that I now noticed were created or reinforced. Links that did not reflect the information that I now noticed were ignored. I basically went through a process of validation by comparing my knowledge to what I perceived as truth. Figure 11 shows a revised mental map of the device.

In my knowledge pool, Figure 11 represents a region referring to a "cellulose applicator." It documents what my mind links to this device based on my past

experiences. More information and experience allowed me to develop a more complex mental map and a more valid picture of the cellulose application concept. Earlier, there basically was not sufficient information to get a complete picture of how the device actually worked. My original picture (Fig. 10) was not necessarily inaccurate, but rather unstructured.

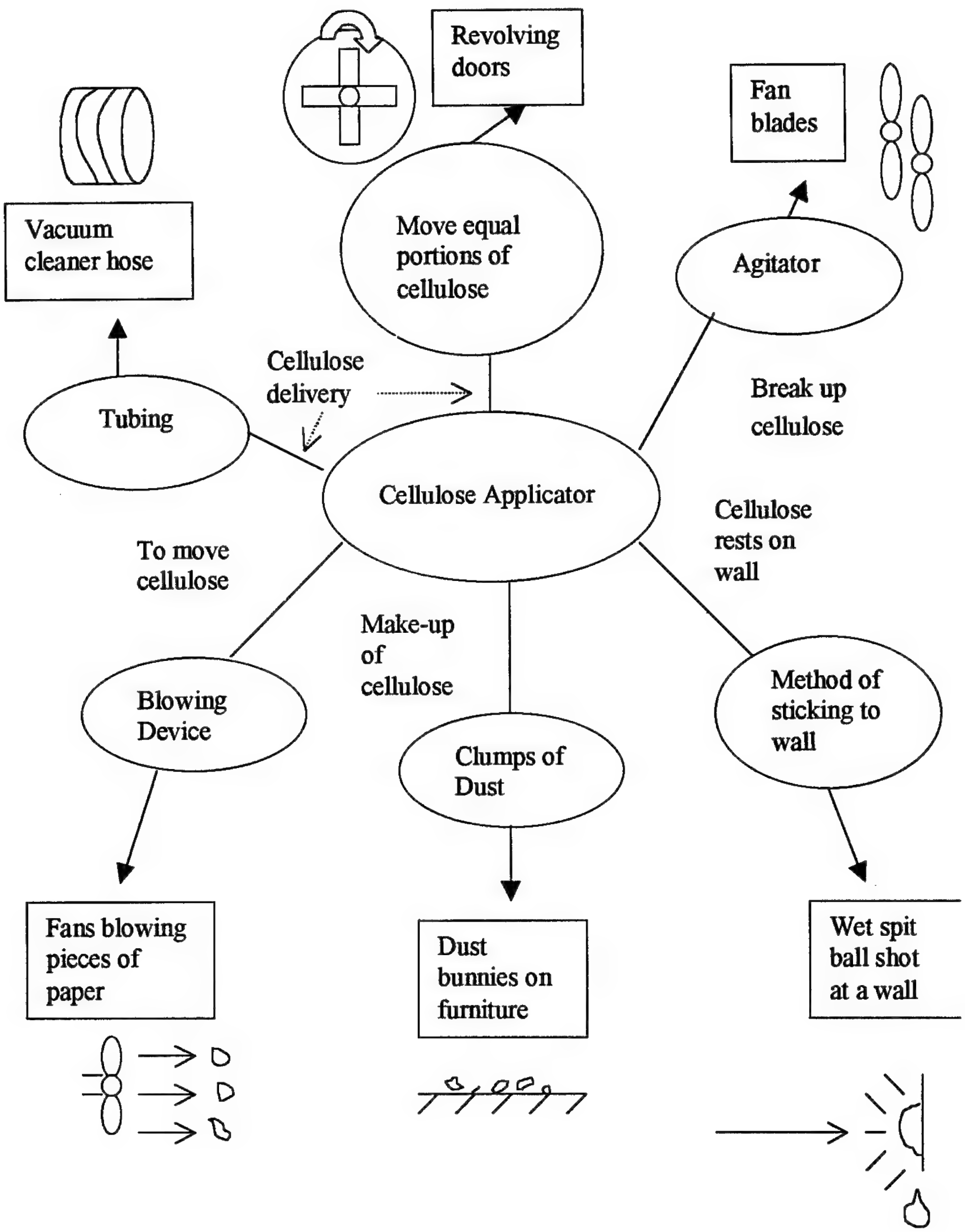


Figure 11: New Mental Map After Observing Application Device

3.1.4 Building on Knowledge with Mental Maps

In actuality, any one of the components in the previous mental map (Fig. 11) can be thought of as a large conglomeration of analogies. Since knowledge builds on itself, an understanding of a new concept is based on the foundation of knowledge a person already has. For example, if I am learning truss design for the first time, much of my understanding will be based on information I've learned for years about the shape of physical objects, mechanical engineering, and basic geometry. I might not consciously recall a particular experience with trusses, but I already may have an association in my mind that many truss shapes are triangular or rectangular. This association probably developed from seeing bridges and buildings, taking geometry courses, or having other related experiences. I might not recall all of these particular experiences as separate and specific analogies, but they have combined over time to create a general understanding of trusses before I have even taken a specific class on truss design.

In regards to the cellulose applicator, I could dissect one component and show various analogous objects that come together to form my understanding of that component. The agitator is one component in the cellulose applicator which breaks up large conglomerations of cellulose so it can be applied in small amounts. Figure 12 is a picture of the agitator set-up in the hopper.

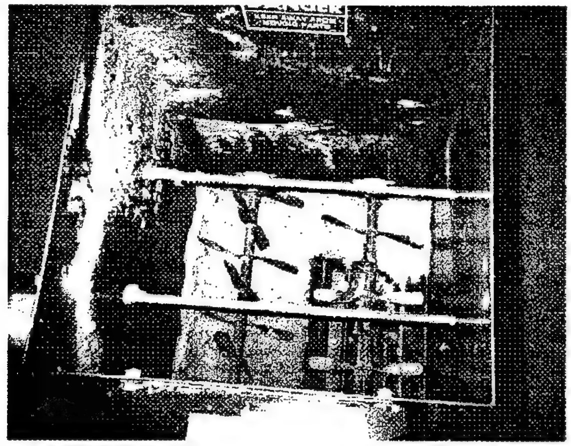


Figure 12: Photograph of Agitator

The propeller shaped blades break up dry, large masses of cellulose and keep the cellulose moving so it can be dropped into a revolving airlock at the bottom of the hopper. This agitator can be represented physically (visually) and functionally in the mind. Figure 13 shows how knowledge of other areas comes together to form a mental picture of the agitator in my mind.

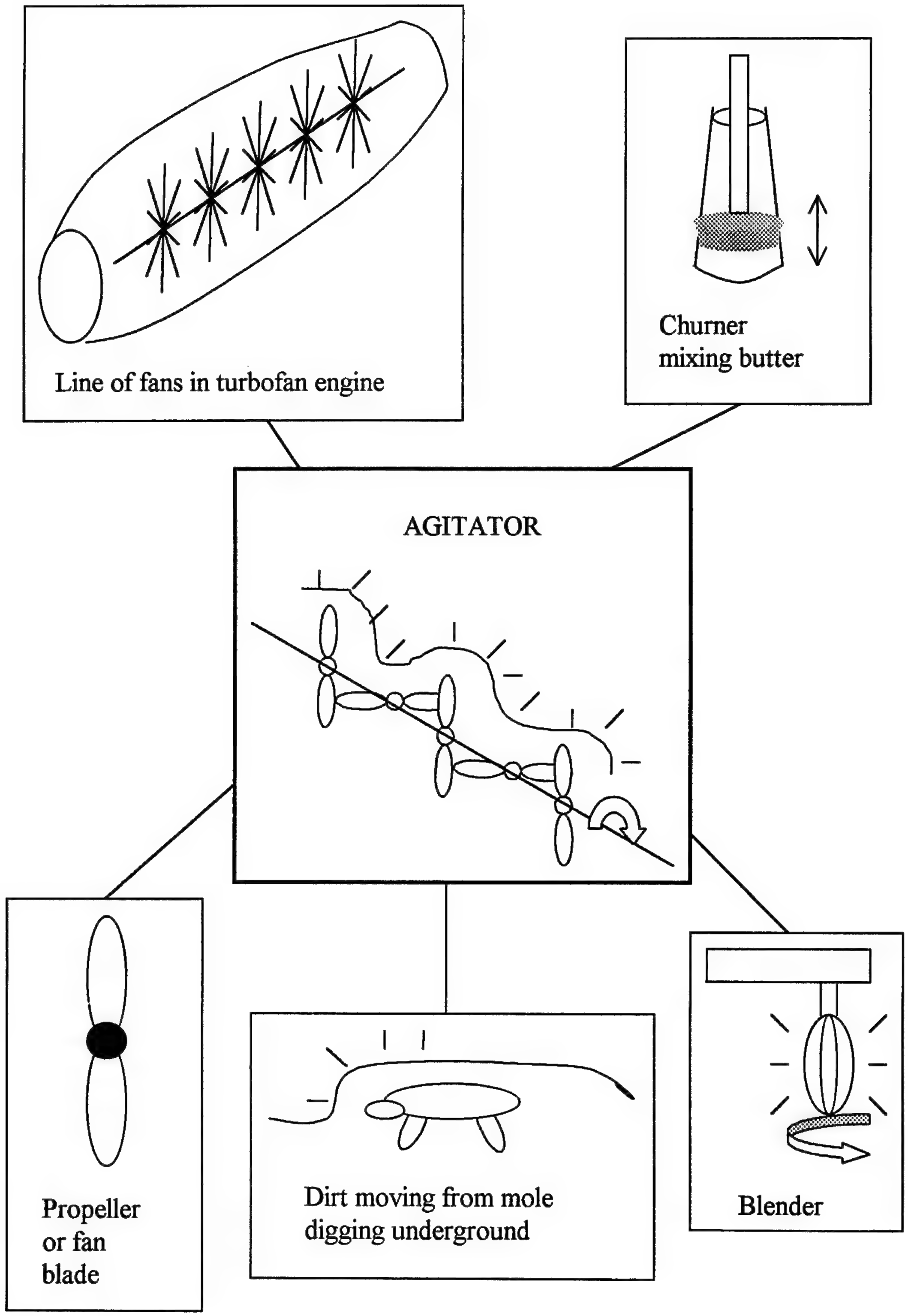


Figure 13: Mental Map of Agitator

3.2 Brainstorming

The analogical process, used with mental mapping, has been described as a means of understanding concepts. It can also be used as a problem-solving process. This process can be used to generate new ideas for design in the same way that a person makes analogies to create a better understanding of a concept in analogical reasoning. We consider "brainstorming" to be a process of using analogical reasoning to generate new ideas in order to solve a problem.

Brainstorming is conducted by an individual or a group. The object of brainstorming is to develop as many ideas as possible in order to solve some problem. The feasibility of the idea is not in question. All ideas that come to mind should be recorded in the brainstorming process. Sometimes, ideas that do not seem feasible will lead to other ideas which are feasible. In a group setting, brainstorming allows people to share ideas.

3.2.1 Creativity through Brainstorming

Earlier in the creativity section, we found that the level of creativity involved with a new idea relied on the level of independence that two or more original pieces of knowledge had. The most creative ideas were found to be those that brought together the most independent knowledge within a given environment. Brainstorming is a key

technique used in design that helps bring together independent knowledge. Through brainstorming, a designer or group of designers hopes to develop as many ideas as possible regarding a specific concept. By having a group of designers working together, a number of different knowledge pools can be brought to bear on the same problem and many more new ideas can be linked in the minds of the participants. Normally, brainstorming is accomplished without bounds, meaning that any and all concepts, no matter how ridiculous, are recorded. In a group of designers, one thought that one person may express could cause another person to associate another experience to that thought. In this way, the group can tap into each other's knowledge and remember old ideas or develop new ideas through association.

Brainstorming does not necessarily have to be done with a group of people, but it is most effective when numerous pools of knowledge can be tapped to gain more ideas from associations that different people have. Figure 14 shows how information from various knowledge pools can be shared in brainstorming and help create many new ideas.

The brainstorming process and the basic process of communication allow information to be transferred from one knowledge pool to another. Since each knowledge pool has its own unique structure of associations and links, that information will become linked differently in each case. For example, if four people are in a brainstorming session and one person states some idea, the other three people will take in that idea and link it to what they already have in their knowledge pools. It will lead them to some other set of ideas in their own minds. Each person will have their unique own links and associations which leads to other ideas of their own.

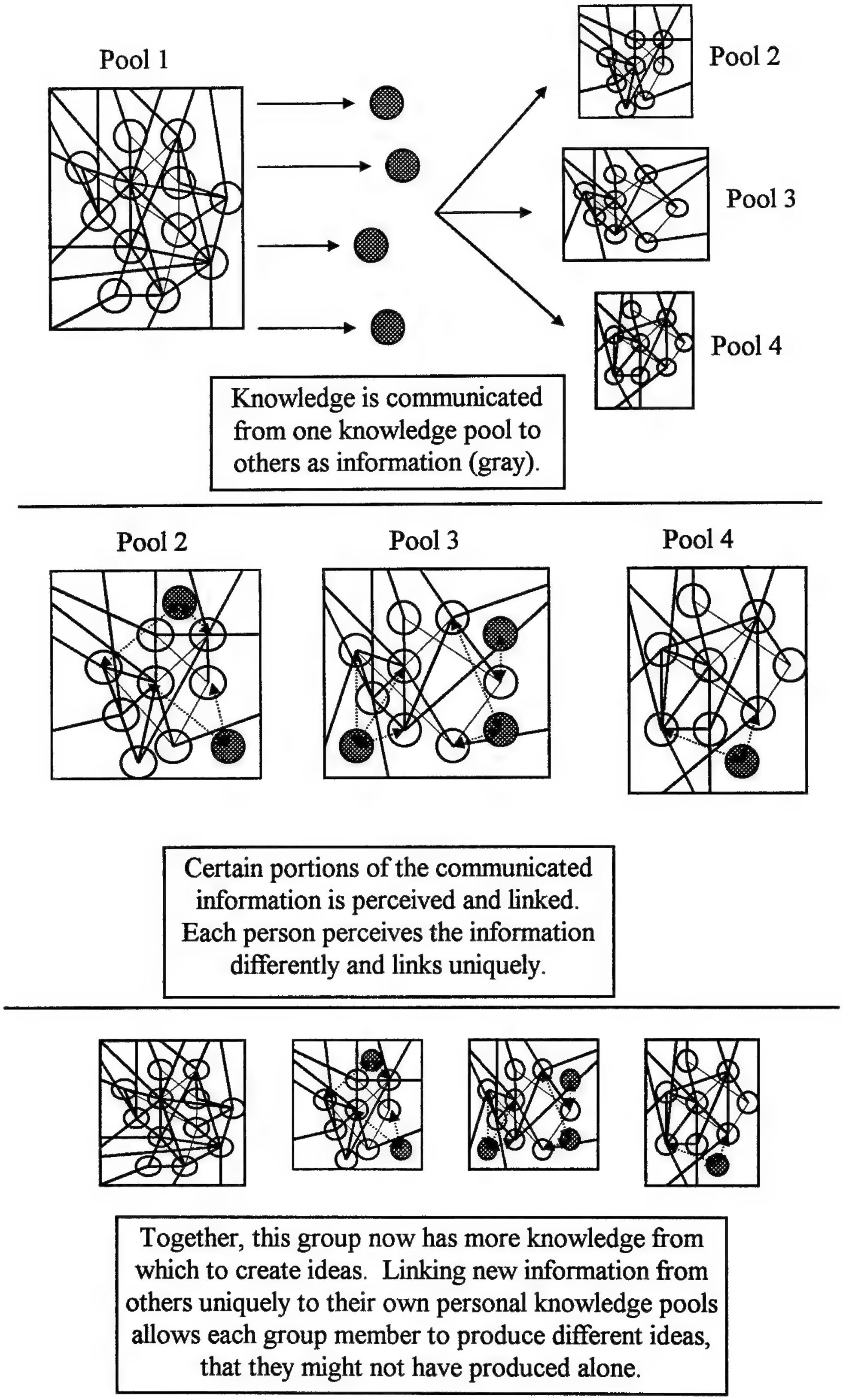


Figure 14: Exchange of Information in Group Brainstorming

3.2.2 Application of Brainstorming Process to Cellulose Application System

This brainstorming process was applied to the cellulose application device by a group of three. Figure 15 is a mental map of the brainstorming process that took place. Since all three of us had separate knowledge bases, we could all tap into different areas of experience and come up with many solutions. The map shows how one idea led to other ideas. All types of ideas were presented, including those that did not seem very rational.

The brainstorming process described is based on creating ideas to solve some problem as opposed to basic analogical reasoning which involves understanding a situation without significant information. Brainstorming can be accomplished over and over to solve numerous sub-problems and generate new ideas. Since it is based on analogical reasoning, it can be used in numerous ways to stimulate creativity during idea generation.

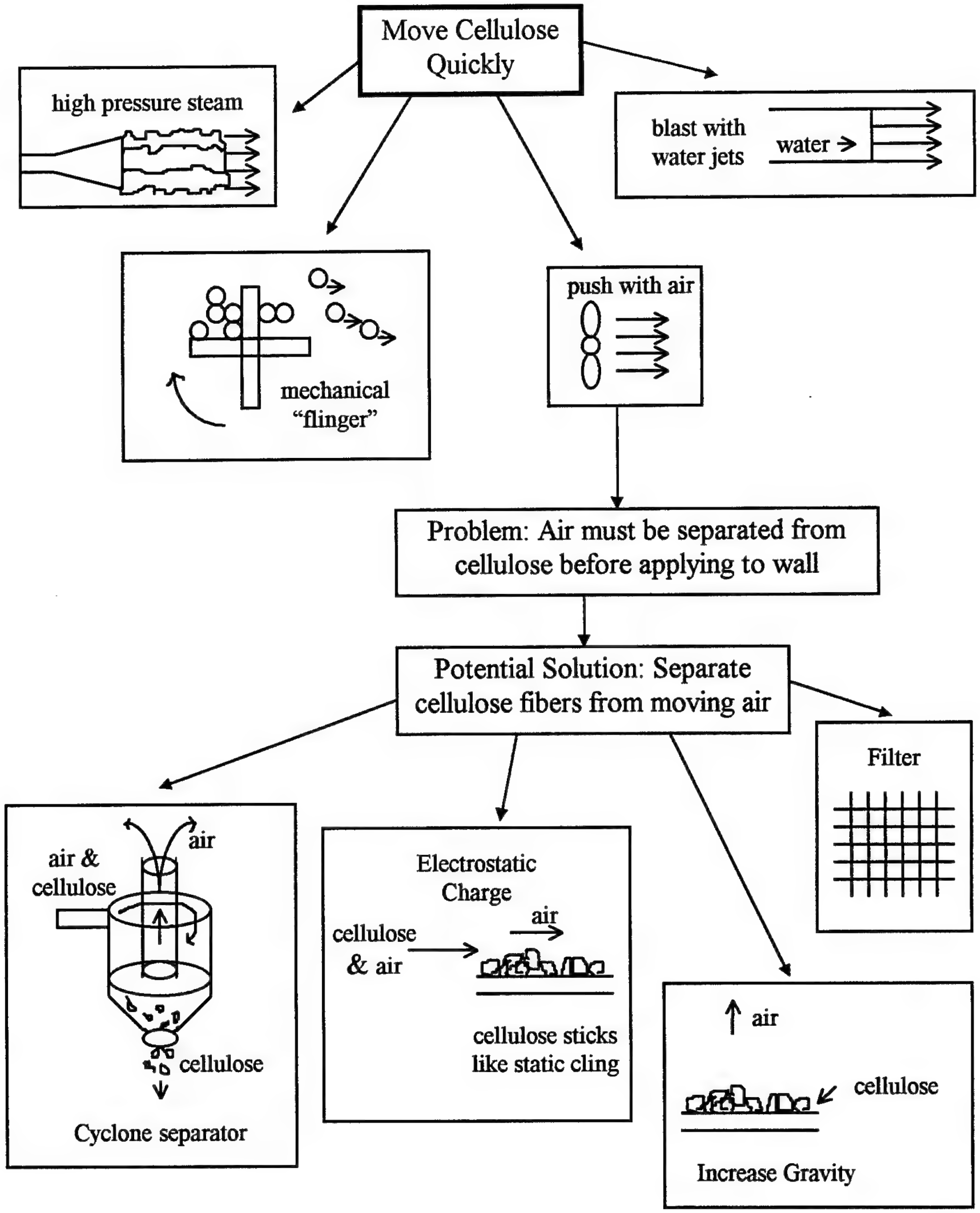


Figure 15: Brainstorming in Cellulose Application Design

3.3 Synectics

The field of study known as synectics has been hailed as a creative design method. The term synectics is derived from the Greek word "synectikos," which means "bringing different things into unified connection" or "bringing forth together" [Roukes 1988]. This root is just about identical to what we've concluded "creativity" is: a linking together of previously dissimilar ideas. Jacob Bronowski states, "a man becomes creative, whether he is an artist or a scientist, when he finds a new unity in the variety of nature. He does so by finding a likeness between things which were not thought alike before" [Roukes 1988].

People seem to view the term synectics in slightly different ways. The methods involved with synectics have basically changed and evolved with time. Nicholas Roukes, author of "Design Synectics," describes synectic thinking as a "process of discovering the links between seemingly disconnected elements" [Roukes 1988]. However, this definition doesn't differ very much from the basic definition of creativity developed in Section 2.1. Others have formed synectics as a kind of theory to enhance creativity in design.

The entire idea was born in the minds of William Gordon and George Price in the 1950s. They became interested in the "processes" that engineers used to create new product ideas more than the actual product itself. They researched this creative process and formed Synectics, Inc. which sought to teach and train others how to solve problems creatively. William Gordon described synectic theory as an "operational theory for the conscious use of the preconscious psychological mechanisms present in man's creative

activity" [Gordon 1961]. Through doing research in a number of test groups, they developed a Synectics theory concluding with the following hypotheses:

1) Creative efficiency in people can be increased if they understand the psychological process by which they operate.
2) In the creative process, the emotional component is more important than the intellectual, the irrational more important than the rational.
3) It is the emotional, irrational elements which can and must be understood in order to increase the probability of success in a problem-solving situation.

Synectics theory was based on tapping the irrational parts of the mind to solve problems creatively [Gordon 1961]. This was mostly due to the fact that many people develop "logical" associations in the head regarding a specific domain of knowledge, which also act as barriers to other ways of thinking. In order to tap into more creative solutions, they must break down their logical barriers and become somewhat irrational or illogical to see other ideas that would otherwise be unseen. The core of Synectics creative thinking has been described as:

1) Make the strange familiar
2) Make the familiar strange

Through this process, a person can look at problems from a strange, new angle and see solutions to problems that would not logically be seen.

Four mechanisms are used in Synectics theory to "make the familiar strange." They are metaphorical comparisons based on analogy:

(1) Personal Analogy - the person looking at the problem becomes the mechanism in question. The mechanism becomes personified. The person imagines they are that mechanism and tries to see it from that perspective, rather than from the outside in.

(2) Fantasy Analogy - looking at a problem from a kind of make-believe view. In this mechanism, all knowledge of the laws of science is suspended and logic is basically discarded. One can look at solving the problem much like a cartoon or fairy tale would.

(3) Direct Analogy - the most commonly used mechanism involving seeing similarities in different processes to solve a problem or create an understanding. Earlier in this paper, direct analogy was explained in depth through the similarities that the sun and planets have with protons and electrons.

(4) Symbolic Analogy - a process of relating visual images to a particular problem. The process of visual mind mapping described earlier basically makes up this mechanism.

These approaches use variations of analogical thinking to enhance the creative thinking process. As can be seen, many parts of the synectic mechanisms branch into other methods already described, such as symbolic analogy (basic mind mapping) and

direct analogy (analogical reasoning). The two mechanisms that have not been investigated already, personal and fantasy analogy, will be investigated in more detail and applied to the cellulose application system.

3.3.1 Application of Personal Analogy to Cellulose Application System

Using personal analogy, I imagined myself as a piece of cellulose fiber that had to be stuck to a wall along with a number of my cellulose fiber "friends." Observing cellulose fiber from the outside, I noticed that the fibers liked to stick to one another in the hose and generally didn't want to change direction easily. Personifying the cellulose, I imagined myself as a clump of fiber about to be flung onto a wall:

> First, I am sitting together with my friends very happily until we are suddenly ripped apart from each other by these huge blades (the agitator) that break us apart. Next, I am pushed through this revolving door and I am blown down this long corridor (hose). I try to keep from moving by holding onto my friends and the sides of the corridor, but the air pushes hard and keeps blowing me and my friends down the corridor. Finally, I see an exit and am flung out of the corridor and wetted down. I quickly notice that the water makes it easier for me to stick to my friends whom I dearly love. I suddenly hit a large wall really hard and hold on to that for dear life. That sticky water makes it easy for me to hold on. A number of my friends are in front of me and behind me and hold on as well.

Together all of us can hold onto this wall much easier. Some of my friends didn't have time to hold onto the wall and fell down. It looks like they are getting picked up and put through the whole experience again.

At first, this personal analog seemed quite strange, but it was also a great deal of fun. In this analogy, I was almost able to sympathize with the cellulose. The analogy personifies how the cellulose is stubborn and likes to stick together. In many designs, we attempted to change direction or separate the cellulose, but it always liked to clog and "stick to each other." The personal analogy definitely helps to make the strange cellulose more familiar and allows for the cellulose to be thought of in a "personal" sense, rather than just as an inanimate substance. From that personal sense, the problem is easier to relate to.

3.3.2 Application of Fantasy Analogy

With regard to fantasy analogy, I looked at the entire cellulose application system from the perspective of a cartoon. I imagined myself as the cartoon character Wile E. Coyote trying to stick this cellulose to a wall. In this state of mind, I was able to imagine a number of solutions to the problem. One solution was to throw a number of little tiny metal pellets into the cellulose and throw the cellulose all over the floor of a house. Then I hooked up a huge electromagnet device to all the walls. I threw a big switch that

turned on the magnet and all the cellulose flew from the floor neatly into the wall cavities. Another solution was that I got a big tube with a trigger like a machine gun and hooked it up to a barrel of cellulose. Then I shot the cellulose in machine gun fashion at the walls. All the cellulose stuck neatly in clumps. Still another solution was that I threw all the cellulose on the floor of the house. Then I bought this scary cellulose eating creature and put it in the house. All the cellulose clumps were scared to be eaten so they ran and stuck to all of the walls for safety.

These fantastic analogies seemed very ludicrous to me at first. However, closer consideration led me to possible solutions to the problem hidden within these crazy analogies. Based on the analogy regarding a super magnet, I conducted research into magnets. I found that there are existing methods in which fibers are directed in certain directions and at various speeds by mixing minute magnetic particles with them and using electromagnets to move the particles. The seemingly crazy analogy opened my mind to other solutions like magnets. Looking deeper into a machine gun type application of cellulose, I found that allowing air to build up in a tube with cellulose and then letting the air escape could create a high enough velocity that cellulose is basically slammed onto the wall. A periodic air pressure build-up could create the speed needed to stick all the cellulose to a wall. I was not able to come up with anything feasible for the last analogy, but maybe that idea will produce a feasible solution with time. In any case, fantastic analogy allowed me to break down logical barriers and open my mind to other solutions outside my limited perception of science.

3.3.3 Increased Linking Using Synectics

Synectics definitely allows a person to tap into other areas of knowledge to conceive solutions which would not otherwise be conceived. By uniting emotion with design, new ideas can be linked together and the creative process can be enhanced. Using methods like personal analogy, a person begins linking emotion and other sections of the knowledge pool that would not normally be linked in the design process. By comparing a particular design situation to another common emotional situation, it becomes easier to understand the problem, like in my personal analogy of the "stubborn" cellulose. Numerous ideas and solutions exist that may not seem logical. But by opening the mind to the "irrational" or "emotional" parts of the knowledge pool, a number of solutions can be discovered and linked to the design problem in question.

3.4 TIPS/TRIZ

In recent decades, there have been numerous studies done abroad in an attempt to discover rigorous methods of creative design. One of the leading theories of creative design is known as the theory of inventive problem solving (TIPS). This theory was originally proposed by the Russian engineer Genrich S. Altshuller in the 1950s. In Russian, his theory was known as Teoriya Resheniya Izobretatel'skich Zadach (TRIZ) and literally translated to TIPS [*History of TIPS* 1997].

His theory is based on the use of technology, rather than psychology, to solve inventive problems. This would be in direct contradiction to the synectics viewpoint which uses psychology to further promote creativity. At the beginning of his studies, he searched for a theory of invention that could have the following characteristics [*History of TIPS* 1997]:

1) Be a systematic, step-by-step procedure
2) Be a guide through broad solution space directing towards the ideal solution
3) Be repeatable, reliable, and independent of psychological tools
4) Be able to access the body of inventive knowledge
5) Be able to add to the body of inventive knowledge
6) Be familiar enough to inventors by following the general approach to problem solving.

Altshuller found that there were a large number of design methods and theories being used to activate searches for solutions, such as brainstorming, focal object method (transposing features of random objects to an object needing improvement), morphological analysis, method of control questions (search directed by a series of guided questions), and synectics based methods. He found that the principle deficiency of these methods was that they were generally unable to solve difficult problems. Methods like brainstorming could create an abundance of ideas but thousands of trials would be necessary to find the best solution for a difficult problem needing an "inventive" solution.

3.4.1 TIPS Levels of Invention and Creativity Ranking

Genrich Altshuller looked to classify what inventive problems were and see how these types of problems were solved. He screened 200,000 patents and found that only 20% of them had what he considered to be "inventive" solutions. The rest were generally straight-forward improvements. In response to this observation, he categorized the solutions to design problems into five levels [*History of TIPS* 1997]:

- Level one - Routine design problems solved by methods well known within the specialty. About 32% of the solutions fell into this level.

- Level two - Minor improvements to an existing system, by methods known within the industry, usually with some compromise. About 45% of the solutions fell into this level.
- Level three - Fundamental improvement to an existing system, by methods known outside the industry. About 18% of the solutions fell into this category.
- Level four - A new generation that uses a new principle to perform the primary functions of the system. Solutions found more in science than in technology. About 4% of the solutions fell into this category.
- Level five - A rare scientific discovery or pioneering invention of essentially a new system. About 1% of the solutions fell into this category

What Altshuller found was that at higher levels of inventiveness for a solution, a broader amount of knowledge was needed and many more solutions needed to be considered. The higher levels required knowledge of other fields to find a solution, outside of the particular specialty in which the problem began.

With regard to knowledge pools, each level of inventiveness would be comparable to the abstract levels of "independence" that were discussed earlier in the creativity section. The independence of original ideas in a knowledge pool is an important factor in the level of a new idea's creativity.

Levels one and two on the inventiveness scale would basically include designs in which knowledge within a particular industry was used. Those that solved these problems did not have to link very independent or dissimilar ideas to come up with solutions. Rather, they used knowledge that is generally available in their particular

specialties to solve the problems. These would not be considered extremely creative solutions.

Level three of inventiveness reflects solutions in which knowledge from other specialties and industries was needed to solve a problem. To come up with these solutions, designers had to get more information from another field of knowledge or relink the knowledge they already had to other fields. These new ideas were more independent beforehand. Links were made within the knowledge pool to other dissimilar areas of knowledge.

Levels four and five reflect solutions in which very independent ideas were brought together to create a solution. In these cases, a new discovery was made which was linked to the design or extremely independent ideas were linked together to attain a new solution. Knowledge from other industries and specialties was used or an entire new specialty was discovered.

3.4.2 The TIPS Method

Altshuller formed teams of people who screened over 2.5 million patents. He used the similarity between patents to further develop the theory of inventive problem solving. One of the basic premises of this theory is that creativity and inventiveness can be taught, and is not just a gift given to certain people. The TIPS philosophy is the result of a number of different discoveries [Sushkov & Wognum 1995]:

1) All engineering systems evolve according to the same regularities, independent of the domain they belong to. These regularities can be used to ease problem solving and enable forecasting of the evolution of an engineering system.
2) Engineering systems evolve through the elimination of various conflicts.
3) An inventive problem is represented as a conflict between new requirements and parameters of an engineering system that cannot satisfy the requirements.
4) Often, an inventive solution to a conflict is outside the domain specific knowledge that the problem was created in.

Basically, an "inventive" approach to problem solving is needed when the problem cannot be solved only using the knowledge available in the domain where the problem was created. Additionally, all engineering systems have universal trends, which are described in TIPS as the laws of engineering system evolution. In this way, certain laws are not restricted to being used in only one domain, but rather in the entire engineering domain. Altshuller and his large team of researchers developed three problem-solving techniques for inventive design:

1) Inventive principles for elimination of engineering conflicts
2) Inventive standards representing a common way of solving certain classes of inventive problems
3) Scientific-engineering effects which organize reuse of physical knowledge

3.4.3 Invention Machine™, a TIPS-Based Software Package

Recently, computer software has been made based on TIPS. This software, known as Invention Machine™, helps a designer to think of new ways to solve a problem through analogy. It uses the same principles as TIPS and generates solutions in sentence form using inventive principles, inventive standards, and scientific effects. Invention Machine™ was used in this research to develop possible designs for the cellulose application system.

3.4.3.1 Inventive Principles and Application to Cellulose Application System

The first problem solving technique uses principles for elimination of engineering conflicts. An engineering conflict occurs when an improvement in one design parameter causes an unacceptable deterioration in another parameter. For example, in a log cutting mill, an increase in log cutting speed will cause an increase in cutting blade wear. The conflict in this case is that improving cutting speed causes an unacceptable deterioration in cutting blade sharpness.

Forty known inventive principles are used as analytical rules to provide guidance in how to solve the problem without negative effects [Altshuller 1984]. For example, in the case of the log cutting problem inventive principle #18 could be used: Use of

mechanical vibrations. Patent number 307986 uses this principle to solve the contradiction: "A method of cutting timber without a saw; in order to reduce exertion needed to insert a tool into timber, cutting is effected by an instrument whose pulse frequency is close to the inherent frequency of vibration of the timber to be cut." The inventive principles provide suggestions to solve contradictions such as this one. Many times, contradictions and applicable inventive principles can be organized in matrix form.

In the case of the cellulose application system, this technique could be used to facilitate solutions to various contradictions in the present design used to affix cellulose in a wall cavity. In the present design, rapid moving air is used to move cellulose through a nozzle and blow it into a wall cavity at a high enough speed so that it will stick to the wall when water is added. However, the moving air not only blows the cellulose into the cavity, but also blows it off the wall. The contradiction is this case is that the air moves cellulose fast enough but also blows it off the wall. Table 1 displays this contraction and lists principles that could be used to solve the contradiction.

What must be improved (reduced):	Velocity of air at wall
What deteriorates:	Speed of cellulose (decreases)
	Potential for clogging (increases)
Applicable inventive principles:	
9 – Preliminary Counter-Action	Carry out some action in advance to counter-act unacceptable affects.
10 – Preliminary Action	Carry out the required action in advance
11 – "The other way around"	Turn the object around by reversing the system
19 – Periodic Action	Transfer continuous action to periodic pulsing action
22 – "Turning harm to good"	Use a harmful effect to obtain a positive effect
28 – Mechanics Substitution	Change a mechanical interaction into a electric, magnetic, electro-magnetic, or other similar interaction
31 – Porous Materials	Porous materials can be used

Table 1: Contradictions and Associated Inventive Principles

These various principles can be used to guide a designer towards creating inventive solutions to a problem. For example, using principle 22 (turning harm to good), the speed of air being used to expel the cellulose could be increased to such a speed that the cellulose is propelled at the wall so fast that it sticks too hard to be blown off by the air. Using principle 19 (periodic action), the air could be delivered at a periodic rate that is enough to expel fast moving cellulose from a nozzle but does not

push enough continuous moving air to blow the cellulose off the wall. Principle 11 (the other way around) could be used to turn the entire system around. Rather than blowing the cellulose onto the wall, the cellulose could be vacuumed to the wall through a material that is porous to air. In this case, principle 31 (porous materials) was also used.

Using Invention Machine™ software, I was able to get similar results. The Invention Machine™ is a program which uses the concepts of TIPS to aid in design. It allows a user to apply either of the three TIPS problem solving techniques towards solving any design problem. It holds a large database of information needed to apply each technique so that a designer does not have to go through numerous outside sources to obtain necessary information. The greatest advantage of this software is that it gave examples to how problems have been solved using specific inventive principles. Appendix A shows an example of Principle 22, Turning Harm into Good or Blessing in Disguise. This example allows a person to use the process of direct analogy to develop new solutions to problems. Another example appears in Appendix B and comes from a solution recommendation developed by Invention Machine Software. This example shows how compressed air could be injected through a porous material to keep the cellulose from clogging. The air would act as a boundary layer between the wall and the cellulose.

The inventive principles definitely allow for the development of more ideas through analogy and associative thinking. It allows designers to think of other ways to find solutions, based on what others have done in the past to solve similar problems. In this respect, knowledge that people have gained in the past can be used to solve future

problems. The links that people have made in the past can be used again to create design solutions in the present.

3.4.3.2 Inventive Standards and Application to Cellulose Application System

Altshuller and his associates developed 76 inventive standards as a means to solve a wide array of universal inventive problems. What they found is that problems from many different domains had similar inventive solutions. They developed inventive standards as a common problem-solving method to solving problems from various fields. The inventive standard is basically a rule that states the needed problem conditions on one side and the necessary transformation on the other side, much like an if-then sentence [Sushkov & Wognum 1995].

Inventive standards can also be applied to the contradictions in the cellulose application system. In the air and cellulose contradiction, one could use the following two standards to gain inventive solutions.

> Standard 3 – "If two substances moving relative to each other have to touch and in so doing a harmful effect arises, the problem is solved by introducing between them a third substance which is a variant of one of the substances given in the specification of the problem" [Altshuller 1984]. This standard implies that some other substance or object should be added between the air and cellulose to solve the problem.

Standard 4 – "If it is necessary to control the movement of an object, one should introduce into it a ferromagnetic substance and use a magnetic field" [Altshuller 1984]. This standard implies that some magnetically attracted substance could be added to the cellulose and then magnetic fields could move the cellulose as needed.

Standard 4 was a very similar solution that I had found earlier using fantasy analogy when thinking of magnets as a feasible way to move and stick the cellulose. The inventive standards can basically be used to apply or change various actions or materials in a problem. It gives a designer ideas as to what other actions can be taken to accomplish a targeted result.

Invention Machine™ software also gave similar results to the problem that air blows cellulose onto the wall and then blows some off the wall. It scrolled me through a slew of different actions that could be taken and different materials that could be used. I have listed a few of the Invention Machine™ software recommendations below.

- To filter interaction between air and cellulose, make action blows changing, varying, pulsed, periodic.
- To filter interaction between air and cellulose, use pauses in action blows and other incompatible actions.
- To filter action blows, multiply air.
- To filter action blows, remove air and obtain required action from cellulose itself.
- To filter action blows, introduce ferromagnetic substance into air.

The software generated many ways to change the problems in order to avoid contradictions. Some of the most feasible solutions listed above were very similar to solutions arrived at through other methods. Periodic pulsing and ferromagnetic substances were both ideas that I arrived at through fantasy analogy. The "multiply air" solution was similar to Principle #22 in inventive standards, Turn Harm into Good. The inventive standards turn out to be an excellent way to make new links and try new actions to gain an objective. Without a list of standards like this one, a designer basically must gain extensive knowledge in innumerable different fields and hopefully find solutions through linking actions in one field to another, within their own knowledge pools.

3.4.3.3 Scientific-Effects and Application to Cellulose Application System

The third technique developed by Altshuller consists of an assortment of scientific-engineering effects. He and his associates found that the more ideal inventive solutions were found through natural phenomenon. Using a natural phenomenon may help avoid a very complex design in one domain of knowledge. However, knowledge regarding which natural phenomenon can be used for specific designs is often unknown by a designer. Many times it is unclear which phenomena would affect some technical function needed by a designer. A technical function is also called an engineering requirement. An example technical function would be to change the size of an object. The TIPS collection of physical effects allows a designer to "bridge the gap" between science and engineering .

The scientific-engineering effect implies that every physical effect is "associated with a multitude of various technical functions the effect may perform" [Sushkov & Wognum 1995]. All natural effects are classified into three groups:

1) Physical
2) Chemical
3) Geometrical

By designating a specific technical function for a design, a designer can search for possible effects that may be applicable. Figure 16 shows the organization of the scientific-effects collection:

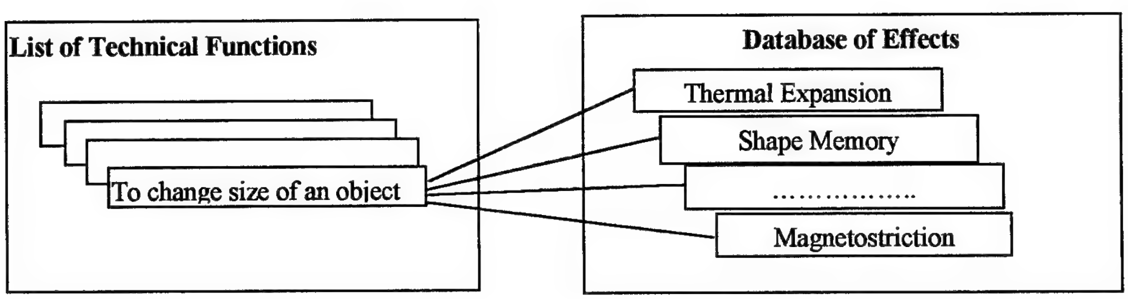


Figure 16: The Organization of the Effects Collection [Sushkov & Wognum 1995]

In the most basic sense, the scientific-effects method allows a designer to tap into a great assortment of scientific knowledge that will help to solve a problem. This large database allows a designer to consider applying science in a way he or she might not have thought of otherwise.

The Invention Machine™ software holds this database of scientific effects. I used the software in the cellulose application system to try to gain information about separating cellulose from air. It had a huge number of interesting effects that could help in separating air from cellulose. I have included two effects that seemed very promising, along with illustrated examples of the effects. Figure 17 is an important recommended physical effect called the Coanda effect.

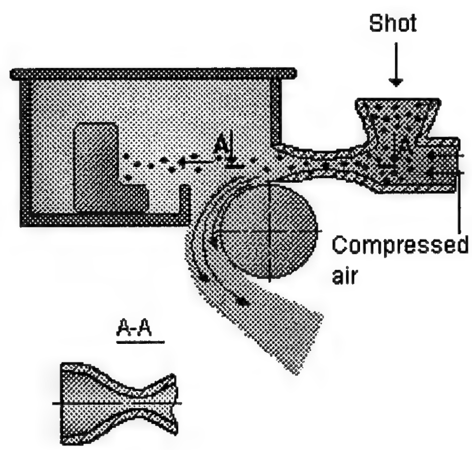
Before I even used the Invention Machine™ software, I "stumbled" upon the Coanda effect when I was experimenting placing a pipe in the air stream of a nozzle. I found that the air stream was induced to bend around the pipe rather than travel straight. I soon made an analogy that this could be used to separate the air from the slightly heavier cellulose as the picture above shows. However, after trying this effect with the actual cellulose-air mixture, I soon found that there was so much cellulose in the stream that it did not act like a typical air stream. Only tiny amounts of air would bend around the pipe while most of the original air traveled straight out with the cellulose.

It was very possible that I would not have "stumbled" upon the Coanda effect idea at all had I not been fooling around with a pipe and putting it in the air flow. However, the scientific-effects database could have given me this idea without having to find it myself through trial and error. While in the end, this effect did not work for the cellulose application, ideas like this one are paramount to creating inventive solutions to problems. Another effect that was recommended was brush constructions. It is a geometric effect explained in the Figure 18.

COANDA EFFECT

As a free jet of fluid (liquid or gas) emerges from a jet nozzle, the stream tends to attach itself and flow over a nearby curved or inclined surface (like a solid cylindrical surface). This is attributable to the jet stream drawing in and transporting nearby fluid molecules. When the number of these molecules is limited by a nearby surface, a partial vacuum is created between the jet and this surface. If the pressure on the other side of the jet remains constant, the vacuum (which is a lower pressure region) will deflect the jet toward the surface itself. This phenomenon is called the Coanda effect. The Coanda effect is very important in fluidics, the technology of using the flow characteristics of liquids or gases to form switches, amplifiers, control systems.

Example of Coanda Effect:
ABRASIVE MACHINING



In abrasive machining, one must separate accelerated abrasive material from an air jet. It is also necessary to direct the air stream outside the chamber.

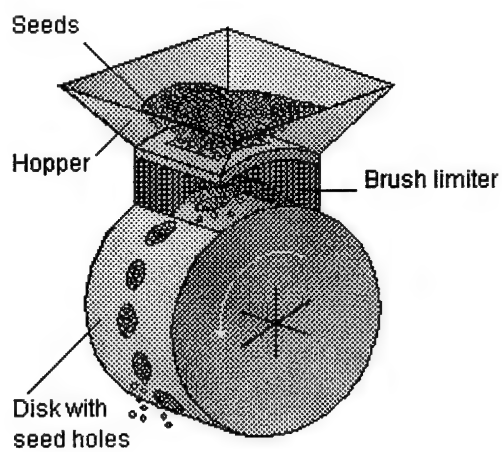
It is proposed to use the Coanda effect in this case. The air-and-abrasive jet is fed tangent to a cylinder surface through a two-dimensional nozzle. The abrasive particles continue moving by inertia in a straight line to the part being worked. The air jet 'sticks fast' to the cylinder surface moving along the convex surface leaving the chamber. A special-purpose ventilation system is rendered unnecessary.
(SU A.c. N 1 098 775)

Figure 17: Coanda Effect and Example from Invention Machine™ Software

BRUSH CONSTRUCTIONS

Brush constructions are sets of oriented components, each having a much bigger linear dimension in one direction than in the other remaining direction(s). Properties inherent in brush constructions are as follows: greater rigidity in one direction, elasticity in another, point or linear contact, ease of control, larger contact surface, the ability to fit the relief tightly and to act directionally, self-adjustment to the surface of interaction. Brush constructions help resolve physical contradictions like permeability - impermeability; soft - solid; point contact - area contact.

Example of Brush Construction:
SEEDING MECHANISM



Brush constructions make it possible to resolve efficiently such contradictions as the requirement for an element to be both penetrable and impenetrable. Thus, beet drills built for large seeds, may be used to sow very small alfalfa seeds. Normally alfalfa seeds are so small that they would not stay in the seed holes of the rotary disk. Most would fall onto its surface, bounce, and roll down to the ground, wasting a large amount of seed. It is proposed to use a brush construction (formed like a hopper) against the disk that lets the disk pass through but limits the spilling of seeds. (SU A.c. N 829 008)

Figure 18: Brush Constructions and Example from Invention Machine™ Software

The idea of brush constructions was another very important idea that I stumbled upon before using the Invention Machine™ software. One day, I was trying to figure out how we could reaccelerate the cellulose had we been able to separate it from air. I placed a clump of cellulose on my hand, flicked it off with my finger, and noticed that it traveled quite fast. I thought of other things that could do the same thing. Basically, I was using analogous thinking to come up with ways to do the same "function" of accelerating the cellulose. I saw a whisk brush hanging up beside me and soon noticed that I could "flick" the cellulose just as quickly using the brush. I next thought of ways I could use a bunch of whisk brushes together that continually "flicked" this cellulose at a constant rate. On the floor, I noticed my small dust vacuum. Looking at it closely, I noticed it had a quickly rotating head of brushes. I turned it on and soon found that it flick would cellulose even faster than I could because of the high speed rotating brushes. From this chain of ideas, we came up with the idea of using brushes to separate the cellulose from air and reaccelerate it. The brushes would allow air to sift through but cellulose would not normally fit through the bristles. A rotating brush could flick the cellulose out at high speed without the large amounts of air.

The brush construction idea became our most promising idea and we have almost developed a science as to how rotating brushes affect cellulose flow. The original idea did not spawn from TIPS/TRIZ, but had we used the scientific-effects sooner, we could have saved a large amount of time. The scientific-effects collection definitely allows a designer to tap into other domains of knowledge that would not be considered otherwise. It allows a designer to expand his or her realm of knowledge without having to search for

hours through other sources of knowledge to get new ideas. Basically, it allows designers to try to link all of these effects to their particular design problem. This new information allows the designer to link new knowledge in his or her knowledge pool without the need to learn all the knowledge of other industries.

3.4.4 Relationship Between Scientific Effects, Principles, and Standards

The relationship between inventive standards, inventive principles, and scientific-effects does not seem very clear, but they all seem to have the same basic foundation. All of these techniques work from the principle of analogous and associative thinking. In every technique, ideas are given that could be used to solve some problem in an inventive way. While Altshuller attempted to develop a method that moves away from psychological approaches such as Synectics, he really developed a method of automating the analogical process and providing analogies based on previous patented ideas.

Many times, the mind will not link a specific object or action to accomplishing a specific task. TIPS/TRIZ presents these objects and actions to a user in one large collection and allows the designer to see a number of possible solutions without having to "discover" them or search through large volumes of information. Using Invention Machine software or other databases, a number of examples can help explain a certain concept. From this point, a designer can make new mental links between certain actions or objects and the design task. In this sense, TIPS/TRIZ enhances creativity by providing several ideas to which a designer can make new links to solve a problem.

Chapter 4: Design Method Correlations and Contributions

The research began with the investigation of creative design methods and their ability to solve a difficult design problem, specifically the design of a cellulose insulation application system. My goal was to explore the extent to which the investigated creative design methods actually enabled creativity in design. The methods of analogical problem solving, brainstorming, synectics, and TIPS were investigated in their ability to produce creative ideas to solve design problems. All of these methods were found to share the same incorporation of analogy as the key step in creating new ideas in the mind. The investigated design methods had similar characteristics that helped to make them "creative" design methods. Associative thinking seemed to be an essential characteristic needed to make a design method creative.

4.1 Connection Between Investigated Creative Design Methods

There are a number of design methods that produce creative results. But what really makes a design method creative? In chapter 2, creativity was defined as a mental process by which a new, independent idea is conceived using knowledge. However, the original "independence" of ideas also plays a key factor in determining the level of creativity. In this way, all new ideas are creative in a sense, but some ideas are more creative than others based on the original independence of the newly associated ideas.

Additionally, the environment in which a new idea is born has a great deal to do with the independence of ideas.

Based on these determinations, **all** methods of generating ideas are creative to some degree. When new, independent ideas are linked together in a pool of knowledge, a creative act has occurred. Any design method that helps provide new ideas to solve a problem is creative. Some methods may help to provide more creative ideas than others. Therefore, as long as a specific design method incorporates the generation of ideas to solve a problem, it is a creative method. However, methods that help associate very independent ideas together will be "more creative" than ones that associate less independent ideas. In this respect, a design method such as Quality Functional Deployment (QFD) is not a very creative design method because it does not involve the generation of ideas to solve a problem. It only involves understanding the problem better. In contrast, the Theory of Inventive Problem Solving (TIPS) is very creative since it involves generating ideas and making links between very independent information that a designer probably never linked before. Even though TIPS was specifically developed to move away from the "psychology "involved in design, it actually provides a huge automated database of generated ideas, so that a person may develop their own analogies.

All of the discussed design methods incorporated generating ideas to understand a situation or to solve a problem. But, these methods also seemed to aid in creating ideas from information that was normally very independent (not closely linked) in origin. In all cases, **the process of generating ideas by association and analogy was key**. New significance and meaning was given to ideas when they became linked in a new way.

These creative design methods all provided a means of linking new meaning to various ideas and applying these new meanings to solving a problem.

4.2 Results of Application of Creative Methods to Cellulose Application System

Each design method was applied in different ways to the cellulose application system. Each design method produced different results. All the design methods enabled creative thinking and enhanced the design process.

Analogical reasoning was applied to the system and helped me to gain an understanding of the entire process based on my knowledge in other areas. Analogical reasoning allowed me to understand the present process of cellulose application by tapping into other areas of knowledge and using them to develop a mental picture of the process. The mental mapping process used in analogical reasoning helped me to realize the key associations I made in understanding the present application system and what areas of knowledge I did not quite understand in developing my mental picture of the process.

Brainstorming allowed my design group to generate numerous solutions to the design problem. By interacting with one another, we were able to tap into each other's knowledge pools and continue generating various ideas that were both feasible and infeasible. Since we all had different perceptions and areas of knowledge, we were able to produce a broad range of ideas. Without the inputs and knowledge from the other

group members, I would not have generated the same broad range of possible design solutions.

Synectics allowed me to use emotion to tap into other solution spaces that I would not have investigated otherwise. Using various forms of analogy, I was able develop new solutions that I had not thought of logically. Solutions involving magnets and machine guns were generated using analogies that did not follow logical thought. My imagination was used to develop fictional stories and scenarios which allowed me to tap into other areas of my knowledge pool that I would not have tapped logically.

The Theory of Inventive Problem Solving was used in numerous ways as a database of analogies which could be applied to the cellulose application system. The inventive standards, inventive principles, and scientific effects databases were all sources of analogies which could be modeled as solutions to this design problem. The Invention Machine™ software generated numerous possible solutions based on solutions developed in the past in hundreds of thousands of patents. The use of the Coanda effect, brushes, filters, porous material, and many other ideas were generated through Invention Machine™.

4.3 Contribution of Creative Method Analysis to the Design Community

The ability to create new ideas has enabled humans to develop countless new inventions, processes, and organizations throughout history. Understanding our ability to come up with new ideas is paramount to being able to hone this ability. The ability to create new ideas comes from the natural process by which most organisms link meaning and significance to an idea through association. This association allows raw information to turn into knowledge by linking it to other ideas.

This research emphasized creative design as a process in the mind of a designer. As was discussed in Chapter 2, creativity is "relative." It depends on the environment in which the creative act occurs. While members of a design community may reject the ideas deemed creative by a particular individual, they will embrace ideas which are new and independent in relation to the current "state of the art" for that community.

This overall design method analysis aided in understanding the basis of creative thought: the development of associations and analogies in a knowledge pool. A definition of creativity was developed that can be used to assess the creative "potential" of other methods. The use of creativity in a practical design problem was tracked to show how these creative methods actually use the process of developing mental associations to form new ideas. An interesting result of this research is that even TIPS was found to be based on the basic process of developing analogies. While Altshuller attempted to create a design method that did not involve psychological approaches, like Synectics, he actually developed an automated method for a person to discover analogies. Analogy has been found to be the key characteristic necessary for creativity.

4.4 Future Research

Further research can be used to develop a greater understanding of the methods by which creativity can be enhanced. Various design methods can be analyzed based on their ability to enable creativity in a designer. Additionally, a deeper analysis of creativity can be conducted to find any other characteristics which are conducive to creativity in design. Other case studies can also be conducted to assess the abilities of these design methods to enable creativity.

Chapter 5: Discovery of Significant, Limiting Problem to Feasible Design

After several attempts at generating feasible design solution concepts for the cellulose application problem from creative methods, we discovered that it was extremely difficult to create a design which delivered cellulose to a wall neatly and firmly. Most of the problems in creating embodiments of solution concepts came from the fact that we knew very little about how cellulose and air flowed together. When mixed together, cellulose and air do not "act" in the same way that they would act separately. The most significant problems we encountered centered in separating the air from the cellulose when it was being applied to the wall. The air will force the cellulose onto the wall at acceptable speeds but will force the cellulose off of the wall as well. However, when the air is taken away, the cellulose does not have sufficient velocity to impact the wall and stick firmly.

We faced many problems such as these in the course of attempting to develop feasible solutions to the design problem. Solutions such as constricted nozzles and devices using the Coanda effect could be used to influence air in certain ways, but would have completely different effects on a mixture of cellulose and air (a multi-phase mixture). When cellulose and air is mixed together as a moving suspension, it has very unique properties which are very difficult to influence or control. These "stubborn" properties made it very difficult to move the cellulose, using air, in such as way that would solve the design problem. Through developing other mechanical designs using

rotating brushes rather than air to accelerate the cellulose, it was further discovered that air was still a significant factor because air in the environment still acts as a drag force to moving cellulose.

The pneumatic suspension and transport of air and cellulose is definitely an area of knowledge that would need further research to develop feasible solutions to this design problem. This gap in knowledge led to further research regarding the pneumatic transport properties of air-cellulose mixtures. The following chapters discuss the scientific investigation of two-phase flow through pipes for air-cellulose mixtures.

Chapter 6: Characteristics of Air-Cellulose Flow

6.1 Multi-phase Flow

Cellulose-air suspensions can be considered “multi-phase” mixtures because they contain elements which are in different phases: gas, solid, and liquid. In the case of an air-cellulose mixture it would be classified as a gas-solid mixture. Multi-phase mixtures can be further classified in various flow conditions by their dispersal pattern. Table 2 shows the classification of complex mixtures from the viewpoint of flow behavior.

<table>
<tr><td rowspan="2">SINGLE PHASE</td><td colspan="5">MULTI-PHASE (GAS-LIQUID, LIQUID-LIQUID, GAS-SOLID, LIQUID-SOLID)</td></tr>
<tr><td colspan="2">FINE DISPERSION</td><td>COARSE DISPERSION</td><td>MACRO-MIXED</td><td>STRATIFIED</td></tr>
<tr><td rowspan="2">TRUE HOMOGENEOUS</td><td colspan="2">PSEUDO-HOMOGENEOUS</td><td colspan="3" rowspan="2">HETEROGENEOUS</td></tr>
<tr><td>LAMINAR TURBULENT</td><td>TURBULENT ONLY</td></tr>
<tr><td colspan="3">FLOW BEHAVIOR AS SINGLE PHASE</td><td colspan="3"></td></tr>
<tr><td colspan="2"></td><td colspan="4">FLOW BEHAVIOR AS MULTI-PHASE</td></tr>
</table>

Table 2: Classification of Complex Mixtures [Govier & Aziz 1972]

This table shows different classifications of multi-phase flow depending on how it is dispersed. This dispersion is most heavily dependent on factors such as flow velocity, mass fractions, and volume fractions of the materials in question. An air-cellulose mixture in transport will fall into the heterogeneous categories. The following are

general definitions, as stated by Govier and Aziz in the previous figure, separating the classifications of multi-phase mixtures with respect to gas-solid mixtures:

Fine dispersion - particles of solid (at submicron particle size) more or less uniformly dispersed in a continuous gas phase

Coarse dispersion - large particles of solid dispersed in a continuous gas phase

Macro-mixed flow pattern - highly turbulent mixture under conditions where neither phase is continuous

Stratified flow pattern - mixture under conditions where both phases are continuous

Most multi-phase research has regarded pipe flow specifically. Figure 19 shows various flow patterns of gas-solid mixtures in horizontal pipes, as discussed by S.L. Soo [Soo 1989]. These patterns can be prevalent in numerous multi-phase mixtures.

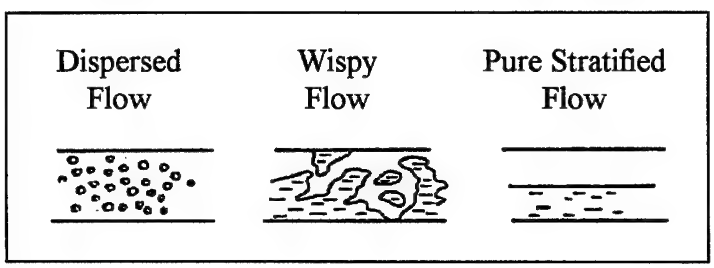


Figure 19: Flow patterns of multi-phase mixtures in horizontal pipes [Soo 1989]

In dispersed flow, the solid is evenly dispersed as particles in the gaseous medium. In wispy flow, there is a wavy interface between the solid and gas. The solid is not dispersed evenly. In pure stratified flow, the gas is completely separated from the solid

and tends to travel above the settled particles at a faster velocity. In vertical pipes, the flow patterns are somewhat similar with some different terminology being used to describe the patterns.

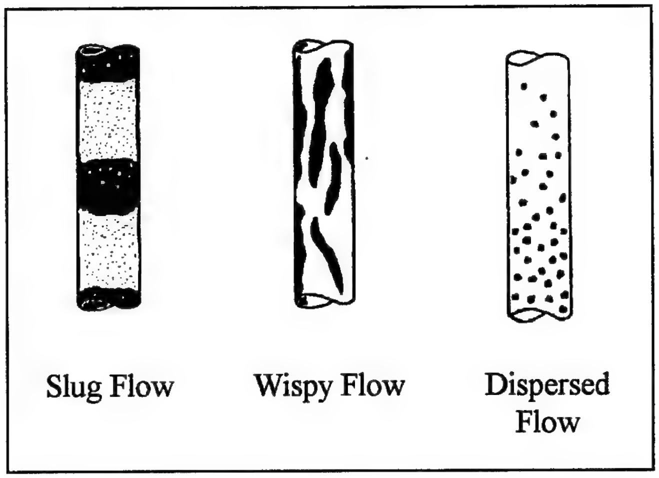


Figure 20: Flow patterns of multi-phase mixtures in vertical pipes [Soo 1989]

In each case, the flow patterns form from different mass fractions of solid with the respect to gas. Figure 20 displays the solid as black and gas as white. Slug flow would appear as slugs of gas and solid. Wispy flow would form as wavy interfaces between the gas and solid. Dispersed flow would involve smaller particles being evenly dispersed in the gaseous medium, similar to that in horizontal pipes.

In industry, pipe flow of multi-phase mixtures is very prevalent. Common plumbing lines often contain the two-phase flow of water and air. Air filtration vents and piping often have two-phase flow of gases and solid particulates. Sewage lines contain multi-phase flows with gases, solids, and liquids. Innumerable flow systems include multi-phase flow in one form or another.

Gas-solid or pneumatic flow systems are used to transport solid particulates using air to suspend and hydraulically convey the material. When large particles or solid pieces are involved, the solids will tend to flow on the bottom of the pipe due to gravity, creating a stratified flow. At high enough velocities, instabilities or turbulence within the carrier phase disperses the solids more evenly in the cross section of the pipe and the flow can display slugs or wave patterns. Figure 21 shows how the cross-sectional dispersion would change with varying air velocity for horizontal flow.

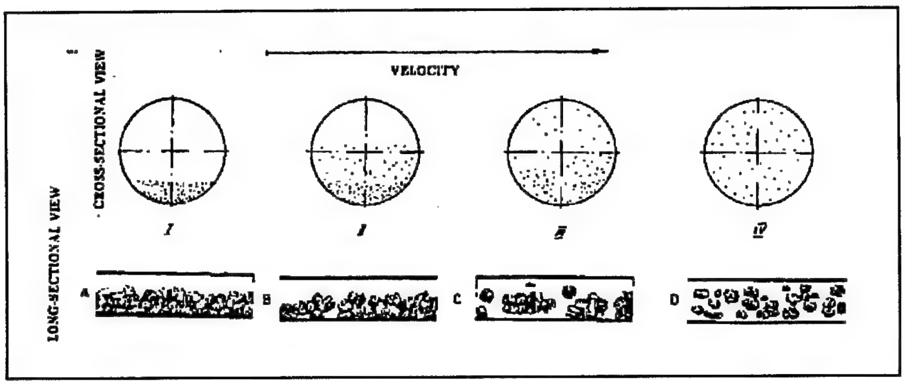


Figure 21: Flow patterns during gas-solid flow in horizontal pipes [Keska 1989]

The mass and volume of the materials in a mixture also play important roles in the flow pattern. Small mass and volume fractions of solids would need to have little air velocity to have evenly dispersed flow patterns. A larger mass fraction of solid would require higher mixture velocities to have dispersed flow. Figure 22 illustrates various flow patterns of coal particles with respect to the volume fraction of coal and velocity. These patterns are similar to flow patterns of air-cellulose mixtures.

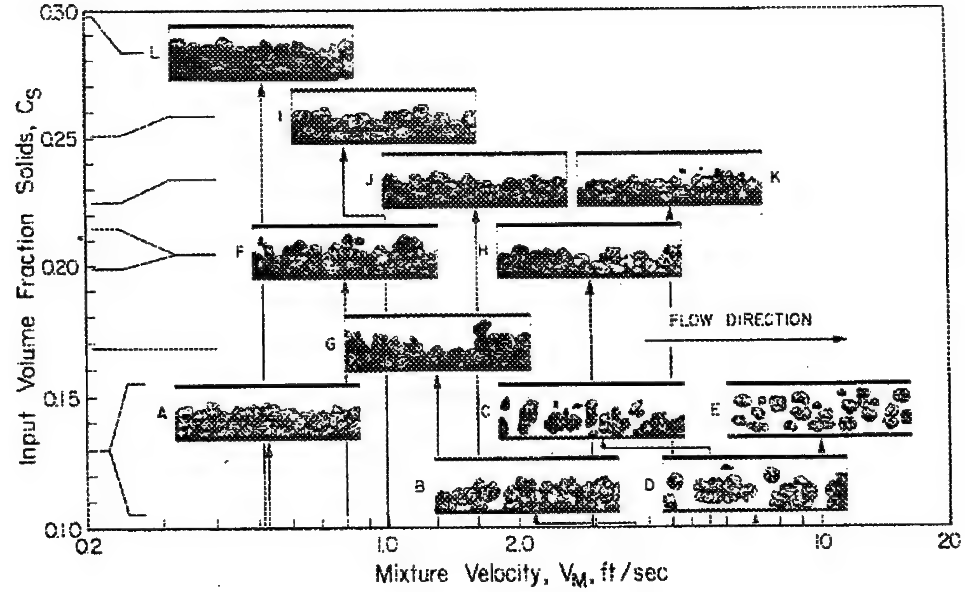


Figure 22: Flow patterns of coal in various volume fractions and velocities [Extended from Worster, British Hydromechanics Research Association 1953]

Mixtures with higher volume fraction of solid coal tend to remain stratified (top left of the Figure) while the lower volume fraction of solid coal flows with more uniform dispersion at high velocities (lower right of the Figure). Basically, velocity, volume fraction, and mass fraction all have effects on the flow patterns of multi-phase mixture. However, cellulose has unique characteristics which make it different from generally non-interactive solids.

6.2 Unique Nature of Cellulose Fibers

So far, the gas-solid mixtures discussed have involved solids which are separate particles dispersed in gaseous mediums. However, the interlocking nature of cellulose fibers makes it unique. Cellulose fibers are acquired from plants and have "interlocking" characteristics much like pieces of Velcro. On a microscopic level, the leafy, interlocking nature of cellulose can be easily seen. Figure 23 displays photographs of cellulosic fibers used for insulation taken with an electron microscope.

Figure 23: Electron Microscope Photographs of Cellulose Fibers
(The short white bar seen in the photographs denotes a distance of 50 μm)

Cellulose fibers naturally have a tendency to cling to one another due to their interlocking nature. This interlocking nature comes about from the fibers mechanically binding at a microscopic level as well as from electrostatic effects. The fibers possess electrostatic

properties and tend to cling together with static charges. These characteristics make it very difficult to predict the flow patterns of air-cellulose mixtures. Cellulose conglomerations or "slugs" in an air-cellulose suspension often have varying sizes and shapes.

Presently, little research has been completed regarding the two-phase flow of air-solid mixtures with highly interactive and interlocking characteristics like cellulose. Experiments analyzing the pneumatic transport of air and cellulose accomplished in this research effort will help to create a greater understanding of this little-known area of knowledge.

6.3 Turbulent, Two-phase Flow

There are always pressure gradients involved with the flow of a medium through pipes. The magnitude of this pressure gradient is often associated with the energy needed to move the medium or mixture of mediums a specific distance. As was stated earlier, air is usually used to convey move solid materials through pipes. The type of interaction the air has with the material and the pipe is important to how much energy is needed to move the material through the pipe. The pressure gradient over a specific length of pipe can be used to compute the associated energy required to move a material through a pipe. Numerous factors must be taken into consideration such as pipe roughness, material density, mass fraction of cellulose relative to air, air velocity, and many others.

In the current research, the flow created through the pipe system was found to be turbulent. Factors such as pipe roughness, pipe diameter, and the air-cellulose interaction contributed to the creation of this turbulent flow. The equation

$$\mathrm{Re} = \frac{Vd}{\upsilon} \quad , \tag{6.1}$$

is used to calculate the Reynolds number for pipe flow. In this research, the Reynolds number is calculated to be greater than 4000 (Re > 4000), in all cases involving only air. Air flow with Re > 4000 is considered turbulent. The two-phase flow of air and cellulose is considered to be in the turbulent region throughout this research.

The following sequence of equations shows how the pressure gradient through a length of pipe can be determined mathematically. The friction factor will help in determining frictional losses in a pipe, which generate pressure gradients. In these experiments, the pipe used was very rough, thus leading to fully rough flow. In fully rough flow, the friction factor is independent of Reynolds number. The friction factor can be determined using the following equation [Colebrook 1938],

$$\frac{1}{\sqrt{f}} = -2 \cdot \log \frac{\varepsilon/d}{3.7} \tag{6.2}$$

leading to,

$$f = \left(\frac{1}{-2 \cdot \log \frac{\varepsilon/d}{3.7}} \right)^2 \tag{6.3}$$

Furthermore, the friction factor is used to calculate head loss in the pipe:

$$h_f = f\frac{LV^2}{2dg} \tag{6.4}$$

Finally, the head loss is used in the calculation of the pressure gradient:

$$\Delta P = \rho \cdot g \cdot h_f \tag{6.5}$$

Chapter 7: Experimental Objectives and Set-up

7.1 Objectives of the Air-Cellulose Flow Research

This research focuses on developing a greater understanding of turbulent, air-cellulose transport. Empirical data is collected regarding the air-cellulose mixture's physical and fluidic properties. Various measurements are made regarding pressure gradients over a length of pipe, by adjusting the mass fractions of cellulose and the mixture velocity. Graphic Moody diagrams and pressure gradient curves are developed to analyze the pressure drops involved in air-cellulose flow. Additionally, the physical dispersion of cellulose in the air-cellulose mixture is analyzed using light extinction measurements to study the formation of cellulose slugs during suspension transport.

7.2 The Fiber Moving Machine

The fiber moving unit is used in the set-up to break up the cellulose, feed it into an airlock, and to blow the cellulose fiber through a hose. This unit is the heart of the experimental set-up and provides the energy needed to move the cellulose through more than 100ft of piping and tubing using air. The machine is designed and built by the Krendl Machine Company®. Figures 24 and 25 are a photograph and internal view of the fiber moving machine loaded with cellulose.

Figure 24: Photograph of the Fiber Moving Unit

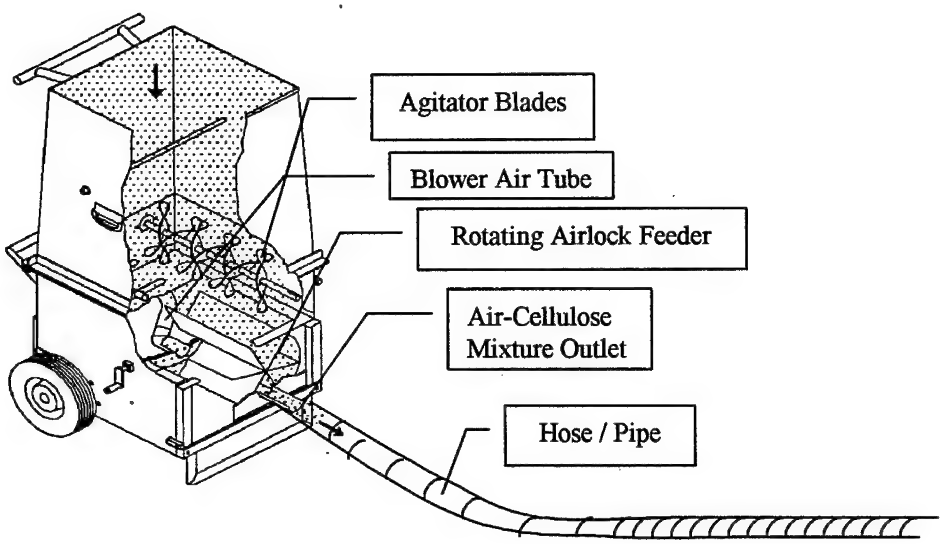


Figure 25: Internal View of Fiber Moving Unit

Cellulose fiber loads into the top of the machine and is agitated or broken up in the open hopper. The fiber moving unit is designed to accept fiber materials into the hopper area of the machine, passing the fibers through a multi-step agitation system, and dropping the cellulose into the rotating airlock feeder. The airlock crankgate feeder adjusts the amount of cellulose to be allowed into the airlock. This airlock crankgate has generic uncalibrated settings ranging from 1 to 8. At gate setting 1, almost no cellulose is allowed into the airlock. At setting 8, the airlock chambers are filled at full cellulose capacity. During testing, settings 4, 5, and 6 were used as standard settings to vary the amount of cellulose entered into the system. From this point, cellulose fiber is then rotated to the bottom of the airlock where air from the blower motor pushes cellulose from the rotating chambers through the hose. Cellulose material and air are prevented from escaping into the machine while in the airlock by six rubber seals which conform to the airlock inner wall as the chambers revolve. The airlock chambers revolve at constant speed. One chamber moves through the airlock approximately every 0.2 seconds, meaning that the injection of cellulose into the air stream occurs at a frequency of 5 Hz. The single, 2-stage blower motor is a high speed unit with low amperage designed to blow air.

A blower speed dial adjusts the speed that the blower blades turn, which affects both the speed AND amount of incoming air. The blower creates an air flow of 0 - 95 CFM. This dial has generic speed settings ranging from 1 to 7 which adjust the blower's speed, with greatest air flow rate at setting 7. These settings were used (1 through 7) throughout testing to provide standard means of keeping the same blower speed in different tests. Figure 26 shows the air mass flow rates associated with each blower speed

setting when the machine is connected to approximately 110 feet of 2" tubing and piping. The air mass flow rates decrease with the addition of cellulose into the flow or the presence of constrictions in the blower air tube. The effects of cellulose and constrictions on air mass flow rates are discussed in experimental results.

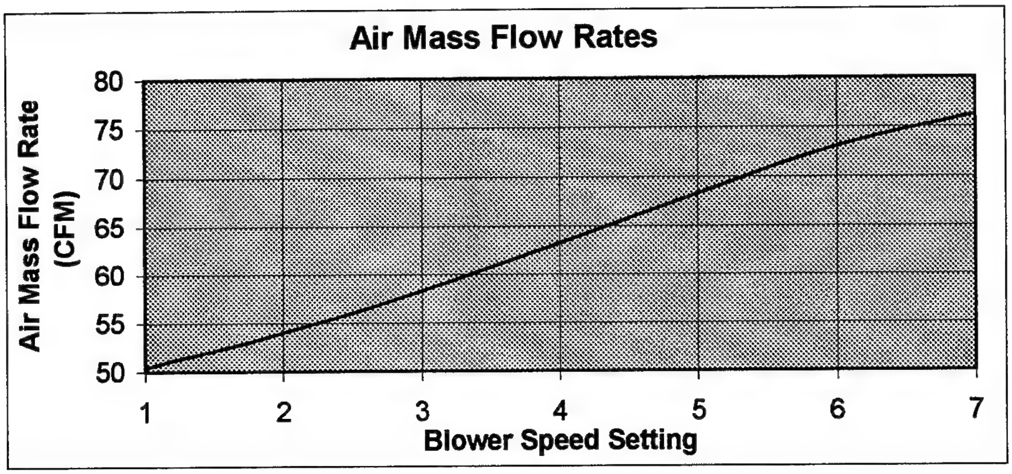


Figure 26: Fiber Moving Machine Air Mass Flow Rates

On the rear of the machine is the blower intake which takes in air. The fiber moving unit was modified with the addition of a venturi tube to measure the air flow taken in by the blower. The venturi tube is connected to a manometer which is used to determine the air flow rate. Figure 27 shows the venturi set-up.

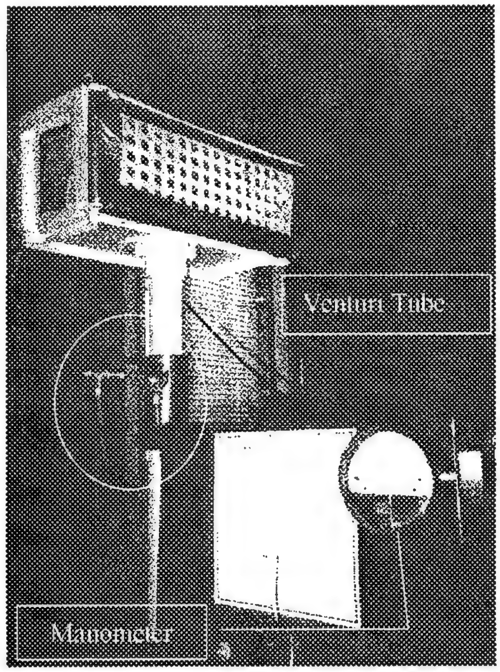


Figure 27: Venturi and Manometer Set-up

The amount of air allowed into the intake of the blower is adjusted with the placement of aluminum constrictions into the blower air tube, which supplies air into the airlock chambers. The two circular aluminum constriction plates used have orifice diameters of 3/4" and 5/8". The blower air tube has a diameter of 2". These constrictions significantly reduce the air mass flow rate. Since the speed and amount of air taken in by the blower cannot be controlled independently by the speed control dial, the orifice plate constrictions allow for a greater range of air flow rates during testing.

In all the testing, the cellulose was first moved through 60 feet of flexible, rough, plastic tubing. This tubing had a roughness (ε) of 0.5" and a diameter (d) of 2.5". This rough pipe helped to provide fully rough, turbulent flow of the air-cellulose mixture. Additionally, the 60 feet of flexible tubing was loosely coiled in different directions to

alleviate the effects of any vortices which might be created by the spinning blower fan. A clockwise spinning blower fan could generate clockwise vortices which would affect the transport properties of the air-cellulose mixture. The tube coiling and high tube roughness ensured that the flow would remain turbulent and unaffected by vortices created by the blower.

In the testing of pressure gradients and mixture dispersion testing, 20 feet of hard, straight, smooth, PVC pipe was used as a platform to provide measurements. The 20 feet of PVC was connected to the end of the 60 feet of rough tubing. Flows going through this pipe remained turbulent as is evident by the high, calculated Reynolds numbers, which will be shown in experimental results. The hard PVC provided for a stable, non-conforming pipe which would not move during testing measurements. In pressure gradient testing and dispersion testing, 30 feet of rough flexible tubing was connected to the end of the 20 feet of PVC and used to return the cellulose flow to the hopper of the fiber moving unit. A screen was placed over the hopper to allow air to escape but keep the cellulose in the hopper. This screen was cleaned periodically to prevent clogging. The cellulose would be recycled back into the system.

In all the testing, the fiber moving unit was run for several minutes before any measurements were taken to allow the blower to heat up and provide a constant temperature of air. The air and air-cellulose flow through the system remained at approximately 23°C once warmed up. Ambient temperatures in the test facility were kept constant using an air conditioning system.

7.3 Mass Fraction Measurement Set-up

As was discussed earlier, a key factor in the transport properties of gas-solid mixtures is the amount of mass of gases versus solids. The mass of air traveling through the system was measured using the venturi tube and manometer set-up. The manometer reads flow rate in inches of water. The venturi tube has a specific conversion equation associated with it as developed by its manufacturer. This equation was used to transform inches of water to flow rate (Q) in cubic feet per minute (CFM):

$$\left(\frac{Q}{100}\right)^2 = \frac{inH_2O}{8.2499} \tag{7.1}$$

thus,

$$Q(CFM) = 100\sqrt{\frac{inH_2O}{8.2499}} \tag{7.2}$$

From this point, the mass flow rate of air was determined using:

$$\dot{m}_a = \rho \cdot Q \tag{7.3}$$

To determine the mass fractions of air and cellulose, the mass flow rates of cellulose through the system, at different gate settings with different blower constrictions, had to be determined. To accomplish this, the cellulose mass flow was measured by transporting the air-cellulose mixture through the tubing set-up and expelling the mixture into a large empty box, during each sampling run. The box was covered with a fine screen to prevent cellulose from escaping but allow air to escape. Each run was timed

and lasted approximately 30 seconds. The weight of the filled box was then measured. The mass of cellulose was found subtracting the filled weight from the empty box weight. The mass flow was determined by dividing the mass by the run time.

Twenty-one cellulose mass samples were taken at each gate setting (4, 5, 6) with no constriction, the ¾" constriction, and the 5/8" constriction for a total of 189 samples. For example, 21 samples were taken for gate 4 with no constriction, next 21 samples were taken for gate 5 with no constriction, and so forth. The 21 samples were made at the full range of blower speeds (1 through 7) to determine if blower speed affected the cellulose mass flow. It was determined that the blower speed had no significant effect on cellulose mass flow. However, the presence of constrictions did have some significant effects on cellulose mass flow, as will be shown in the results. The gate setting had the greatest effect on cellulose mass flow, since the gate directly controlled the amount of cellulose permitted into the system. The blower speed setting and constrictions only affected the amount and speed of air put into the system.

7.4 Pressure Gradient Testing

The pressure gradients for flow through a fixed length of pipe were measured to obtain data on the friction factors and pressures associated with mixtures of air and cellulose. Figure 28 visually describes the general set-up used to take measurements.

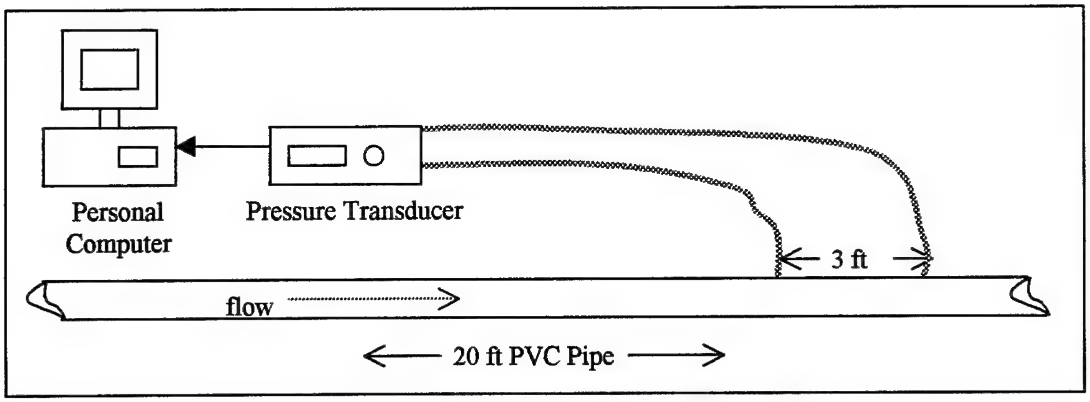


Figure 28: Pressure Gradient Testing Set-up

The fiber moving unit was connected to 60 feet of rough 2.5" pipe which was connected to 20 feet of smooth 2" PVC pipe to measure pressure drops. The transition between the 2.5" tubing and 2" PVC was smooth to alleviate clogging problems. A digital pressure transducer measured the pressure difference and was connected to the pipe with Tygon® tubing to 2 small protruding pipes on the top of the PVC. The protrusions used in testing were 3 ft apart. The first protrusion was located 15 ft from the beginning of the PVC pipe. The end of the PVC pipe was connected to 30 feet of 2.5" rough tubing which led back to the fiber moving unit. Moving the location of the measurements on the PVC pipe did not have any notable effects on the pressure drop. Pressure drop measurements were the same at different locations on the pipe, as long as there was 3 ft of separation between the measurement sites.

The pressure transducer was connected to a personal computer which recorded results using a LabView© virtual instrument interface with a controlled sampling rate and run time. The pressure transducer was a Type 510B transducer produced by MKS Instruments, Inc. The pressure transducer communicated data to the computer via a 12

bit digitizer card. Pressure gradient samples were taken every 0.01 seconds with run times of 3 minutes, for a total of 18,000 samples per run. The pressure transducer measured at a range of $\pm 19.3 \times 10^{-3}$ psi. When connected to the 4096 bit LabView© interface, the resolution was 0.00942×10^{-3} psi. From these recorded samples, the average pressure, RMS pressure, and friction factor were determined. Friction factor (f) was calculated using the following equation:

$$f = \frac{2d\Delta P}{LV^2 \rho} \tag{7.4}$$

First, the entire set-up was tested using only air. A 3" PVC was also used to provide a greater range of results to ensure the set-up was feasible and would generate acceptable results. The 3" PVC was ONLY used in this phase of testing and was not used for air-cellulose runs. One 3 minute run was performed at each blower speed with the 5/8" constriction, the ¾" constriction, and no constriction. These runs were conducted with both the 2" and 3" PVC pipe. The resulting friction factors were compared to the Reynolds numbers to generate a Moody diagram, which appears in the experimental results.

Air-cellulose pressure measurements were taken in the same manner as previously described, except gate settings were also adjusted to alter the mass of cellulose added into the system. One 3 minute run was performed for each blower speed (1-7) at gate settings 4, 5, and 6 with all the constriction settings (5/8", ¾", none). A total of 63 runs were performed and recorded. Results from these runs were used to generate air-cellulose Moody diagrams and pressure vs. velocity curves.

7.5 Mixture Dispersion Testing

The dispersion of the air and cellulose in the pipe was measured using a cross-sectional laser set-up. Figure 29 visually represents the laser set-up.

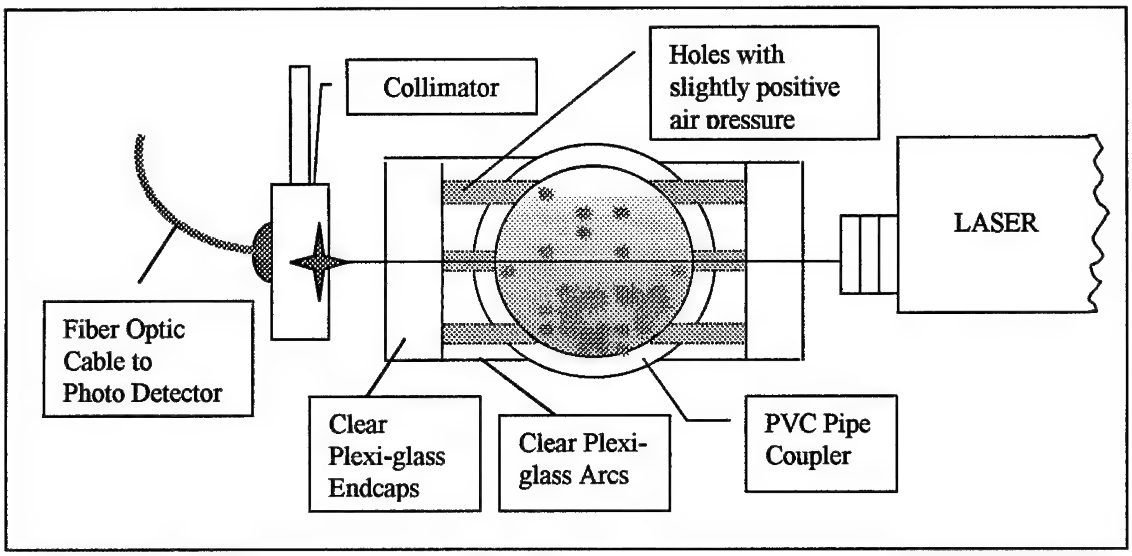


Figure 29: Cross Sectional View of Mixture Dispersion Laser Test Set-up

The laser set-up was designed as a method to qualitatively determine how much cellulose is present in a certain area of the pipe at certain times. Laser light shining through the pipe is collected on the other side by a collimator. High amounts of laser light collected by the collimator would indicate a low concentration of cellulose in the stream, while lower laser light would indicate more cellulose, since it would scatter and absorb the incident laser beam.

The PVC pipe was fitted with a PVC coupler with parallel holes on each side as seen in the set-up. One set of holes is positioned at the top, middle, and bottom of the pipe coupler. Clear, arced, Plexiglas pieces were connected to this PVC and had matching holes. Clear Plexiglas endcaps covered the end of the holes and allowed laser light through but restricted any air flow out of the holes. The 630 nm red laser beam radiated through these holes to the other side where the collimator received the laser energy and directed it to a photo detector via covered fiber optic cables. Each Plexiglas arc had additional perpendicular outlet openings for each of the holes which were attached to an air compressor with air hoses. The air compressor provided very low positive pressure of about 5 psi, which kept the holes from clogging with cellulose but did not affect the flow within the pipe.

The photo detector was connected to a personal computer which recorded results using a LabView© virtual instrument interface. The computer also controlled sampling rate and run time, as in the pressure gradient testing. Laser intensity samples were taken every 0.002 seconds (500 Hz) with run times of 30 seconds for a total of 15,000 samples per run. The photo detector sent a voltage signal of 3 volts at maximum laser intensity. At 3 volts the laser beam was unobstructed. The detector measured 0 volts when no laser energy was received. When connected to the 4096 bit LabView© interface, the resolution was 0.00488×10^{-3} V. From these samples, the average voltage and RMS voltage were determined.

Four 30-second runs were performed at blower speeds 1, 4, and 7 at gate settings 4 and 6 with all the constriction settings (5/8", ¾", none) at the top, middle and bottom of the pipe. For example, four runs were performed at blower speed 1, gate 4, with ¾"

constriction, at the top of the pipe. Next, four runs were performed at blower speed 4, gate 4, with ¾" constriction, at the top of the pipe and so on. A total of 216 runs were performed and recorded. At gate setting 4, the cellulose mass flow rates varied from 15 to 21 g/s while they varied from 45 to 55 g/s for gate setting 6. Appendix C displays the exact air and cellulose mass flow rates at each gate setting, constriction size, and blower speed.

During each run, the RMS voltage was calculated by the computer. Additionally, the amount of times the laser was completely blocked (voltage = 0 V) was also recorded. When voltage equaled zero, enough cellulose was present in the pipe to completely block out the laser beam from the receiving collimator. Generally, a large slug of cellulose traveling through the pipe would block the laser, but fine pieces of cellulose would only diffuse the laser energy without completely blocking it. The amount of times voltage equaled zero was determined in percentage and called "Percent at Zero Volts." This term helped in determining the percentage of the time that dense slugs of cellulose were present in the system.

Due to the large variations of cellulose densities flowing through the system, it was extremely difficult to assess the exact mass or volume of cellulose necessary to block all laser light. Hence, this portion of the testing was essentially qualitative, rather than quantitative. During testing, ten second laser test samples were taken at 400 Hz for every test and saved. These samples were analyzed to show exact times of voltage fluctuations. Results from the laser test runs were used to generate statistical histograms and other graphs which show the densest locations of cellulose in the pipe and the presence of slugs of cellulose. Additionally, the frequencies of slugs were determined

using Fast Fourier Transforms and compared to the frequencies of slugs coming directly out of the machine to determine if the slugs were self-induced or created by the discrete injection of cellulose by the airlock.

Chapter 8: Experimental Results and Discussion

8.1 Mass Flows and Mass Fractions

Various mass flows of air and cellulose were present depending on gate settings, blower speed settings, and the presence of constrictions. Figure 30 shows the average cellulose mass flow rates for each setting. The results are the average of three samples taken at each blower speed. Small mass flow variations are visible at each gate setting and constriction size through the range of blower speeds.

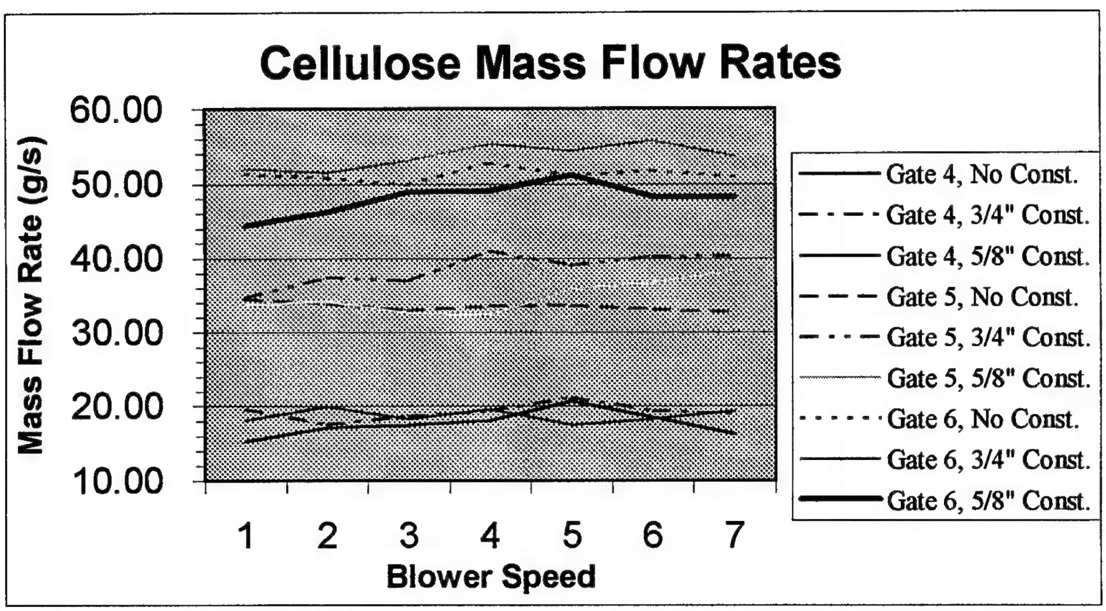


Figure 30: Cellulose Mass Flow Rate Versus Blower Speed

Table 3 shows the average measured cellulose mass flows sorted by gate setting and constriction size. The average mass flow was averaged over blower settings 1-7.

Airlock Gate Setting	Constriction Size	Average Mass Flow (grams/sec)	Standard Deviation
4	none	17.75	1.93
4	3/4"	19.32	1.34
4	5/8"	18.71	1.07
5	none	33.73	0.54
5	3/4"	37.86	2.34
5	5/8"	33.76	1.40
6	none	51.21	1.09
6	3/4"	53.27	1.57
6	5/8"	47.94	2.63

Table 3: Average Cellulose Mass Flows

Table 3 shows that the airlock gate setting had the greatest effect on cellulose mass flow. The larger gate setting introduced more cellulose into the system and thus increased average cellulose mass flow. The size of the air constriction also had some impact on the mass flow but values tended to only differ by 1 - 5 grams per second with changes in constriction size. The standard deviation column shows the deviation for the 21 samples taken in each category. Deviations are likely to have occurred due to the innate randomness of cellulose densities introduced into the air stream and some variation caused by changes in blower speed.

Air mass flow was affected by the presence of constrictions. The 5/8" constriction resulted in lowest air mass flows, while no constriction allowed for highest air mass flows, due to the increased pressure loss created by the addition of cellulose

added to the system. Gate settings also had some effect on the air mass flow. A small gate setting of 4 would allow little cellulose into the stream and allow for higher air mass flows, while a high gate setting of 6 would result in less air mass flow since more cellulose was introduced. Appendix C shows total mass flows of air and cellulose in bar graph form, sorted by gate setting. These graphs show the changes in air and cellulose mass flow at each blower speed, gate setting, and constriction size.

The mass fractions of air and cellulose for each factor were determined by dividing the individual mass flows by the total mass flow:

$$\text{cellulose mass fraction} = \frac{\dot{m}_{cellulose}}{\dot{m}_{cellulose} + \dot{m}_{air}} \tag{8.1}$$

Table 4 shows the ranges of **cellulose** mass fractions in regards to gate settings and constrictions over the full range of blower speed settings. With smaller sized air constrictions, the cellulose mass fraction increased, since air mass flow decreased. While the cellulose mass flow would not necessarily change, the cellulose mass fraction would change with a change in air mass flow. Higher blower speeds lowered the cellulose mass fraction. The overlapping ranges of cellulose mass fractions provided for continuous mass fraction representation from 28 - 80 %.

Airlock Gate Setting	Constriction Size	Cellulose Mass Fraction Range
4	none	28 - 40 %
4	3/4"	40 - 53 %
4	5/8"	45 - 56 %
5	none	46 - 60 %
5	3/4"	59 - 68 %
5	5/8"	63 - 71 %
6	none	58 - 72 %
6	3/4"	67 - 77 %
6	5/8"	69 - 80 %

Table 4: Cellulose Mass Fraction Ranges

8.2 Pressure Gradient Testing

In order to verify the set-up for the pressure gradient testing, the resultant pressure drops from air flow through the system were compared to those expected for an ideal smooth pipe. As described in the experimental set-up, friction factors were derived from the measured pressure gradients and used to create a Moody plot. Equation 8.2 was used to develop a curve for an ideal smooth pipe with no roughness ($\varepsilon = 0$), relating friction factor to the Reynolds number [Colebrook 1938].

$$\frac{1}{\sqrt{f}} = -2 \cdot \log\left(\frac{2.51}{\mathrm{Re}\sqrt{f}}\right) \tag{8.2}$$

Solving for Reynolds number, this lead to,

$$\mathrm{Re} = \frac{2.51}{\sqrt{f}} \cdot 10^{\frac{0.5}{\sqrt{f}}} \tag{8.3}$$

Using the Reynolds number equation, the ideal smooth pipe curve was created on a Moody diagram. Figure 31 is a Moody diagram showing the Moody curves for the 2" and 3" test pipe with various constrictions.

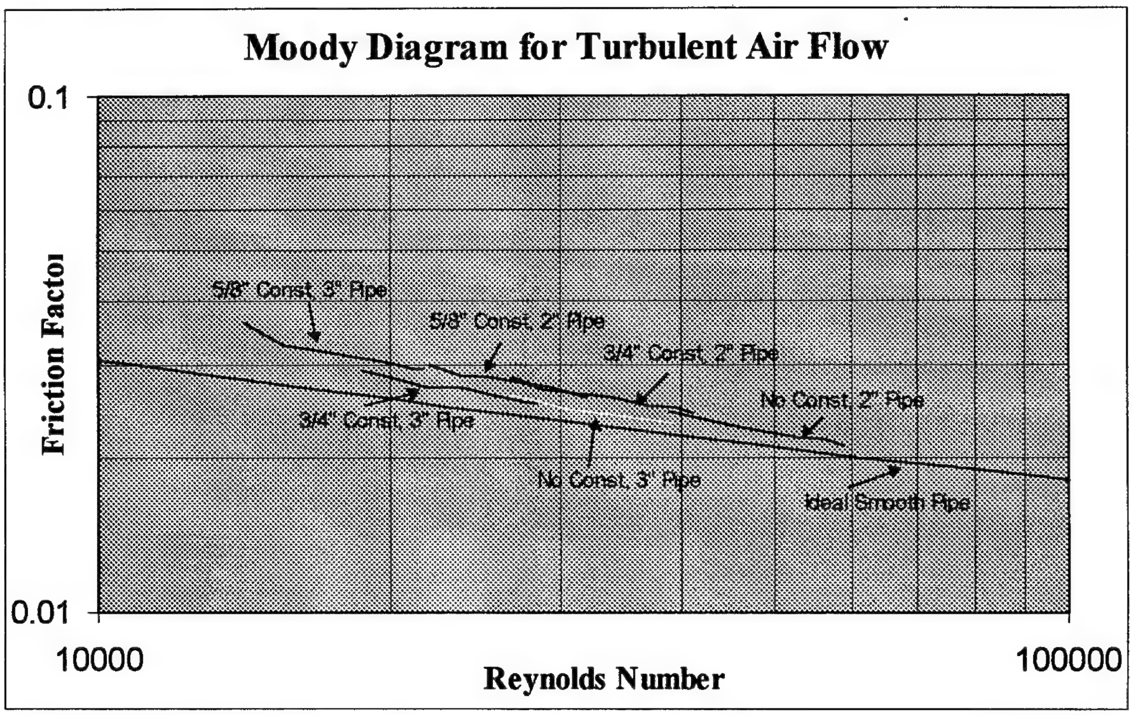


Figure 31: Air Flow Moody Diagram Curves

The labels on the Moody diagram, such as ' X" Const, Y" Pipe,' describe results with the X" constriction size and the Y" diameter pipe. The lower curve across the entire diagram

represents the curve for an ideal smooth pipe. The results show that the measurements fall in the same area as the ideal smooth pipe curve. However, the curves have a 5% to 15% difference from the ideal curve. This difference was most likely due to small air leaks into the system which bypassed the venturi meter, thus giving a slightly low velocity measurement for the air. The system was continuously inspected and repaired for air leaks, but small leaks still existed. Another cause for this difference was the fact that the PVC was not a perfectly smooth pipe and would have some roughness. Roughness would cause friction factors to be slightly higher than ideal, as is the case in the Moody diagram. In general, the resultant curves all tended to fall in the same areas and had common differences in relation to the ideal smooth pipe curve.

The venturi meter measured the air flow rate in inches of water. By adding 0.2 inches of water to all of the air flow rate measurements, the resultant curves fell right on the ideal smooth pipe curve. Appendix F shows the adjusted Moody diagram. This would indicate that the venturi meter consistently made measurements 0.2 inches of water below the actual value, caused by leaks into the system. In the rest of the experiment, this error was accounted for by adding 0.2 inches of water to the flow rate measurements.

The addition of cellulose into the air flow changed the Moody curves significantly. Since the viscosity of the air-cellulose mixtures was unknown and the density of cellulose in the air flow constantly changed, viscosity and density of air was used in Reynolds number and friction factor calculations. Figure 32 is a Moody diagram of the air cellulose mixture.

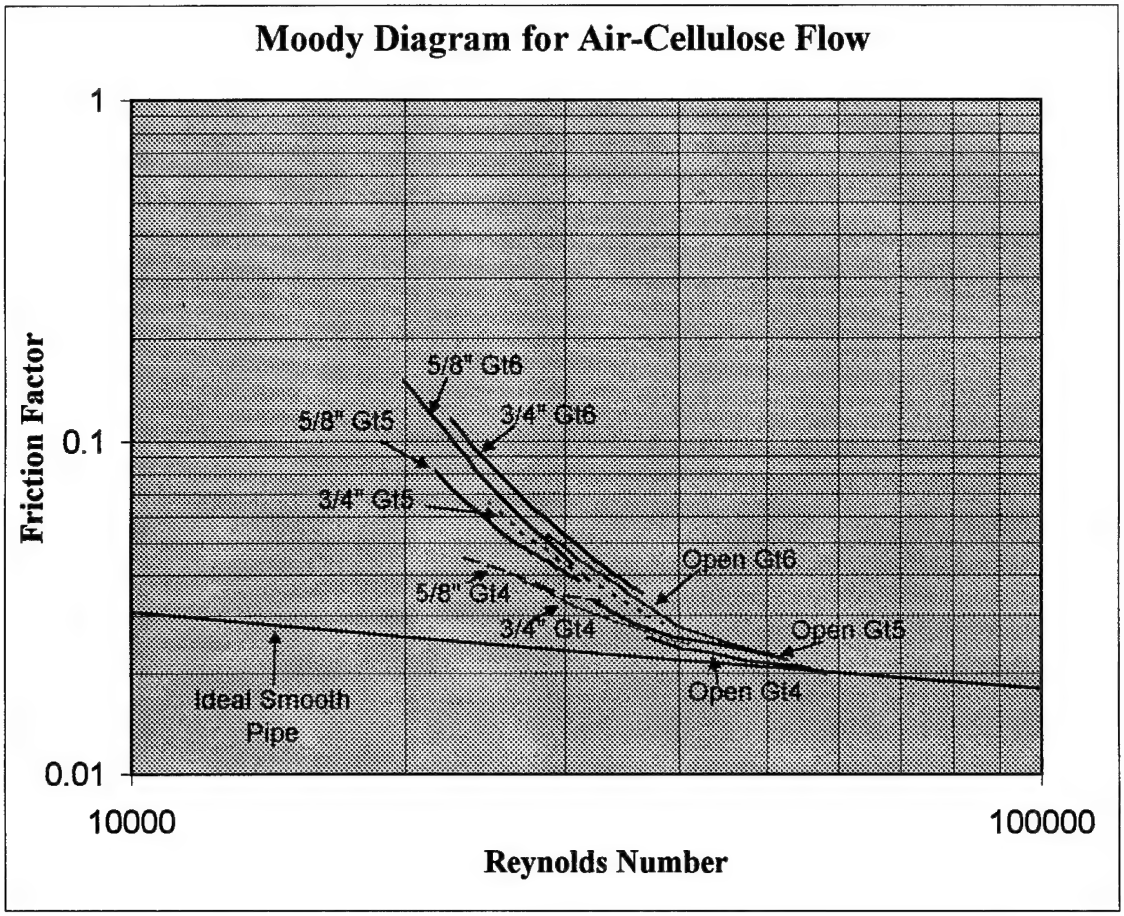


Figure 32: Air-Cellulose Moody Diagram Curves

The labels in Figure 32 describe the constriction size and gate setting. For example, "Open Gt4" describes results for gate 4 with no constriction. The results show that air-cellulose flow with low air mass flows tended to deviate sharply from the ideal smooth pipe curve for turbulent air flow. The 5/8" constrictions resulted in the lowest air mass flows and the highest deviations from the ideal smooth pipe curve. Results of runs with no constriction (Open) show much less deviation from the ideal smooth pipe curve. In these cases, the greatest amounts of air mass flow were present in the system.

The graph in Figure 33 was developed without assuming density and viscosity equal to that of air. This graph compares the pressure gradient to the volume flow rate per unit pipe area (Q/A). Research in the area of multi-phase systems often uses graphs such as these in order to prevent the problem of assuming densities and viscosities.

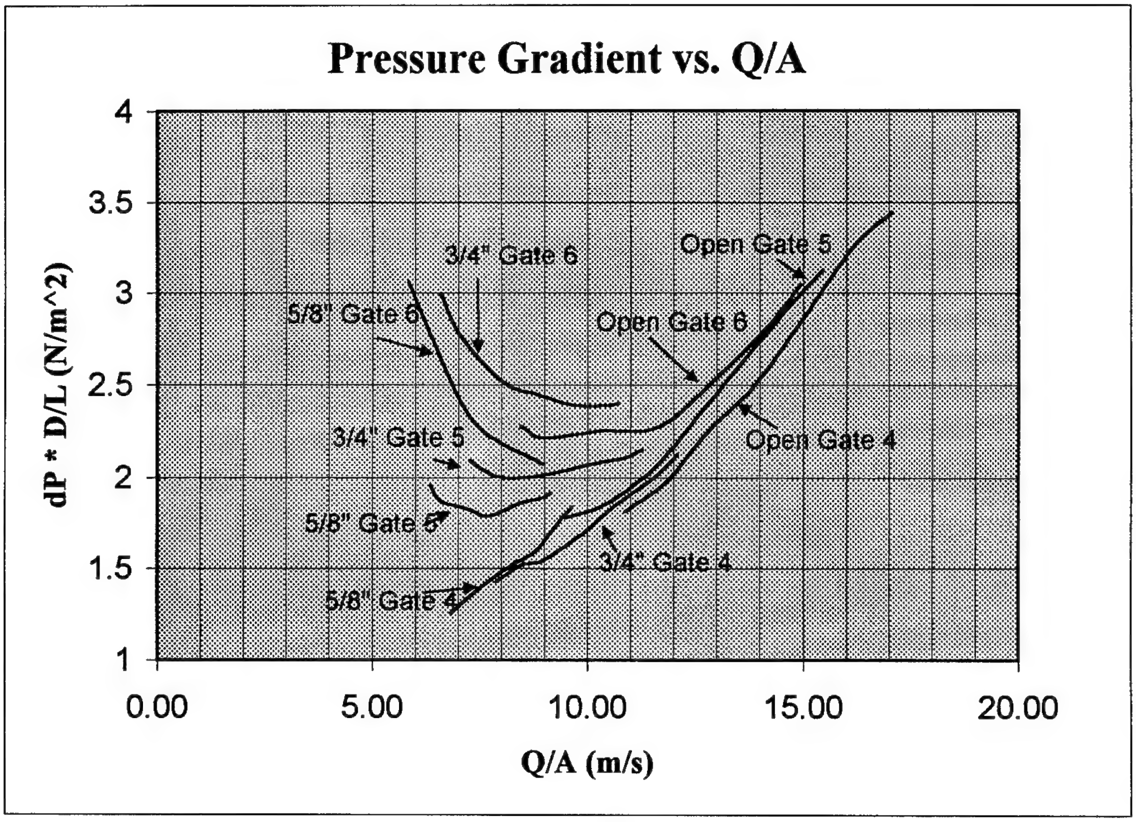


Figure 33: Pressure Gradient vs. Q/A of Air-Cellulose Flow

Figure 33 shows the relation of pressure gradient to volume per area for the different gate settings and constriction sizes. In normal turbulent air flows in pipes, pressure gradient decreases with respect to air velocity. The case of gate 4 with no constriction (Open Gate 4) most closely resembles this type of pattern. In this case, there is a very low

cellulose mass flow and mass fraction. With higher gate settings like gate 6, more cellulose is present in the mixture and the mass fraction of cellulose is higher. In these cases, pressure gradient actually tends to go up with decreases in air velocity. Additionally, cases which had the highest total mass flows, such as those with gate setting 6 (Appendix C), tended to have the highest pressure gradients with respect to air velocity.

Other studies into two-phase flows of gas-solid mixtures discussed similar results. Many results show that higher mass fractions of solids tend to cause increases in pressure gradient for decreased air velocities. Figure 34 shows results of research concerning the flow of cress seed in air in a 1-inch pipe:

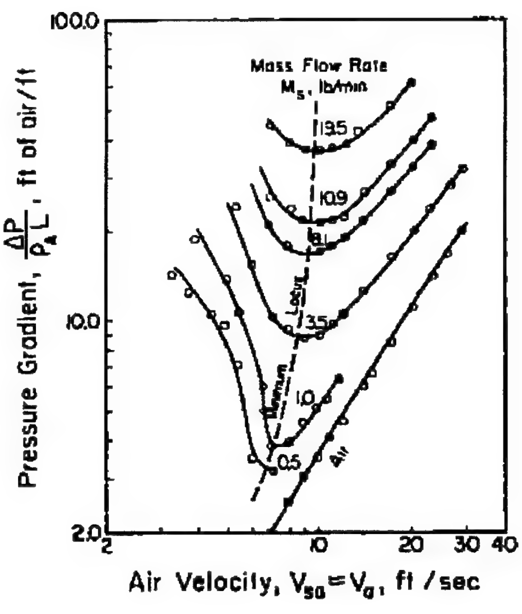
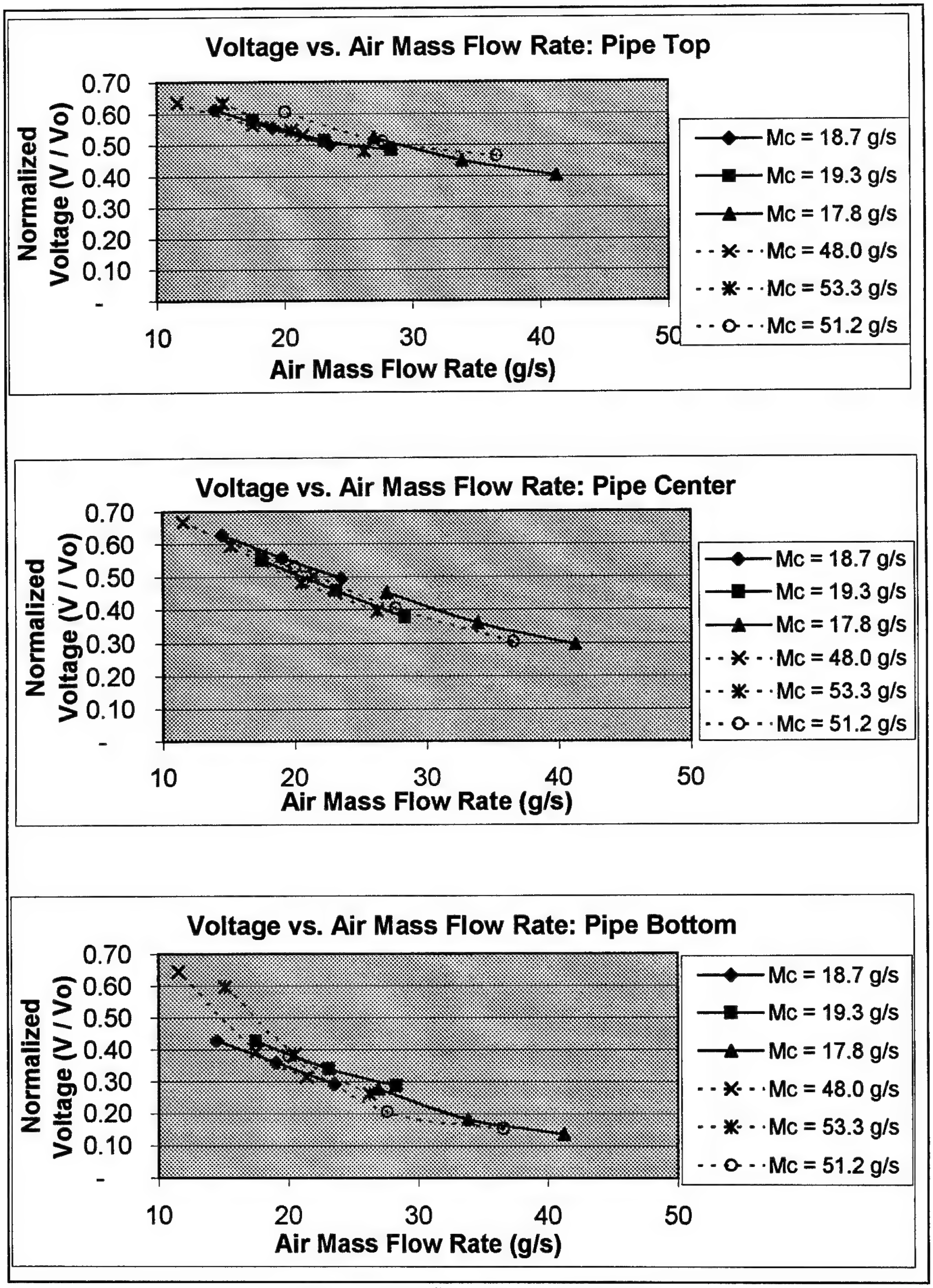


Figure 34: Pressure Gradient vs. Air Velocity for Cress Seeds in Air [Clark 1952]

While cress seeds do not have the same interlocking nature as cellulose fibers, the pipe flow of cress seeds in air is quite similar to that of cellulose and air. In both cases, higher total mass flows tend to have higher pressure gradients and curves tend to have the same U-shaped curve pattern.

8.3 Mixture Dispersion Laser Testing

Mixture dispersion laser testing helped to show the physical properties of the air-cellulose mixtures as they moved through the pipe. Measurements were obtained at the top, middle, and bottom of the pipe. The key measurements recorded included the average voltage and the percent at zero volts. The receiving laser collimator registered 3 volts when the laser was unobstructed and 0 volts when completely obstructed. Due to the large variation in cellulose densities flowing through the system, the exact cellulose density needed to completely obstruct the laser could not be determined. The percent at zero volts helped to show the amount of time the laser was completely obstructed by slugs of cellulose. Appendix D shows tabulated results of the tests for each gate setting, constriction orifice size, and blower speed. Figure 35 graphically displays the differences in the normalized voltage at the top, middle, and bottom of the pipe.



"Mc" = mass flow rate of cellulose

Figure 35: Normalized Voltage vs. Air Mass Flow Rate for Mixture Dispersion Testing

The results in Figure 35 show that varying the mass flow rate of cellulose from about 20 g/s to 50 g/s did not cause any large changes in the average voltage vs. air mass flow rate curves. Additionally, there was a general decrease in voltage with increased air mass flow rates. With more air present in the system, it would be assumed that higher air mass fractions would always cause higher average voltages in the laser measurements, since the air would not obstruct the laser. However, this is not the case. This is actually due to changes in the physical structure of cellulose formations as they traveled through the pipes with different air and cellulose mass flows.

With higher cellulose mass fractions, the cellulose began moving in larger, dense, interlocking "slugs" with pockets of air usually separating the slugs, rather than the cellulose being dispersed evenly in the air flow. At low cellulose mass fractions, the more evenly dispersed cellulose in the air stream would cause a uniform "blocking" of the laser energy much like a cloud of smoke. At high cellulose mass fractions, the larger slugs would momentarily block the laser energy and then "cleaner" pockets would allow most of the laser energy through. Overall, the average laser voltage would be higher due to the higher amounts of "clean" air in between the slugs of cellulose.

Ten-second test samples help to show the dispersion of cellulose with various mass fractions at different parts of the pipe. From these samples, histograms were created to show the laser voltages most common during every test. Figure 36 shows a sample taken at the top of the pipe with no constriction orifice at gate 4, blower speed 7, with its associated histogram. With these conditions, there was a cellulose mass fraction of approximately 30%. This sample provides an example of a uniform air-cellulose dispersion occurring at the top of the pipe.

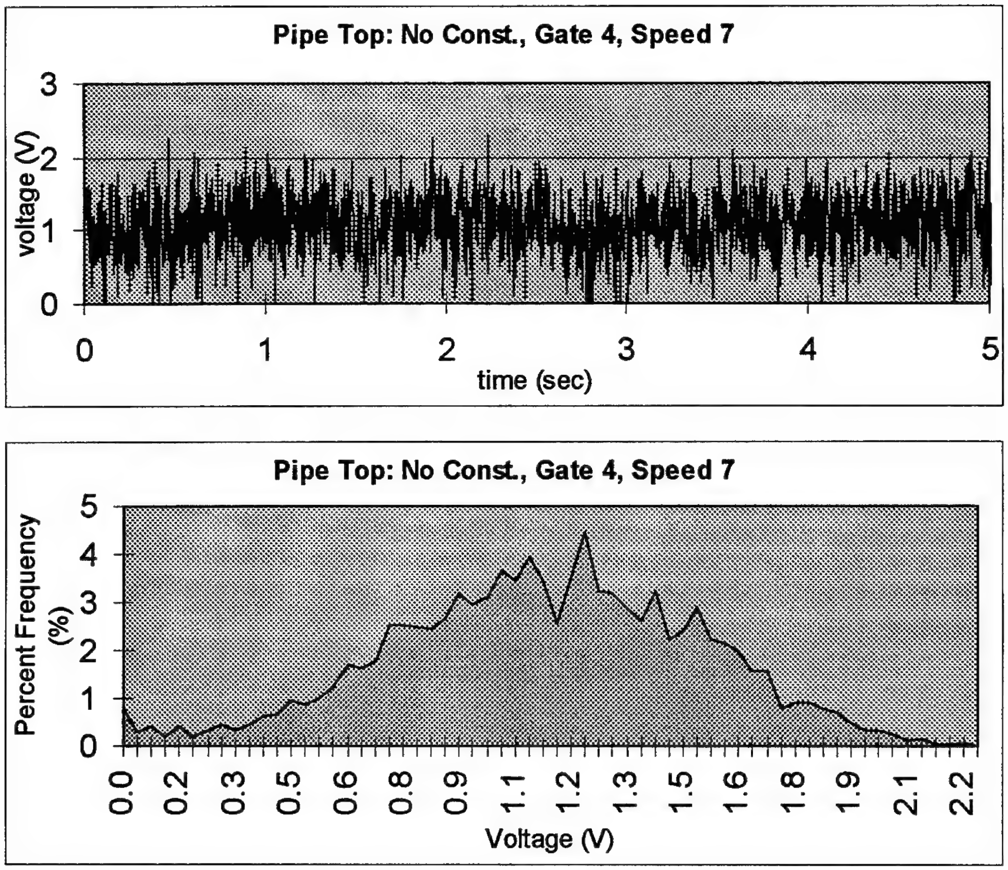


Figure 36: Test Sample of Evenly Dispersed Air-Cellulose Mixture

In this test, the voltage never measured higher than 2.25 volts suggesting that no "clean" areas of air were present. Additionally, the laser energy was rarely fully obstructed by cellulose (0 volts). In general, the average voltage was about 1.2 volts. The histogram shows a fairly normal distribution of voltages between 0 and 2.2 volts. In general, this sample shows how fine particles of cellulose were evenly distributed in this case at the top of the pipe.

Figure 37 displays test results which show flow characteristics of wispy flow. This is a sample from the center of the pipe with a ¾" constriction orifice, gate 6, speed 7, and an approximate cellulose mass fraction of 65%.

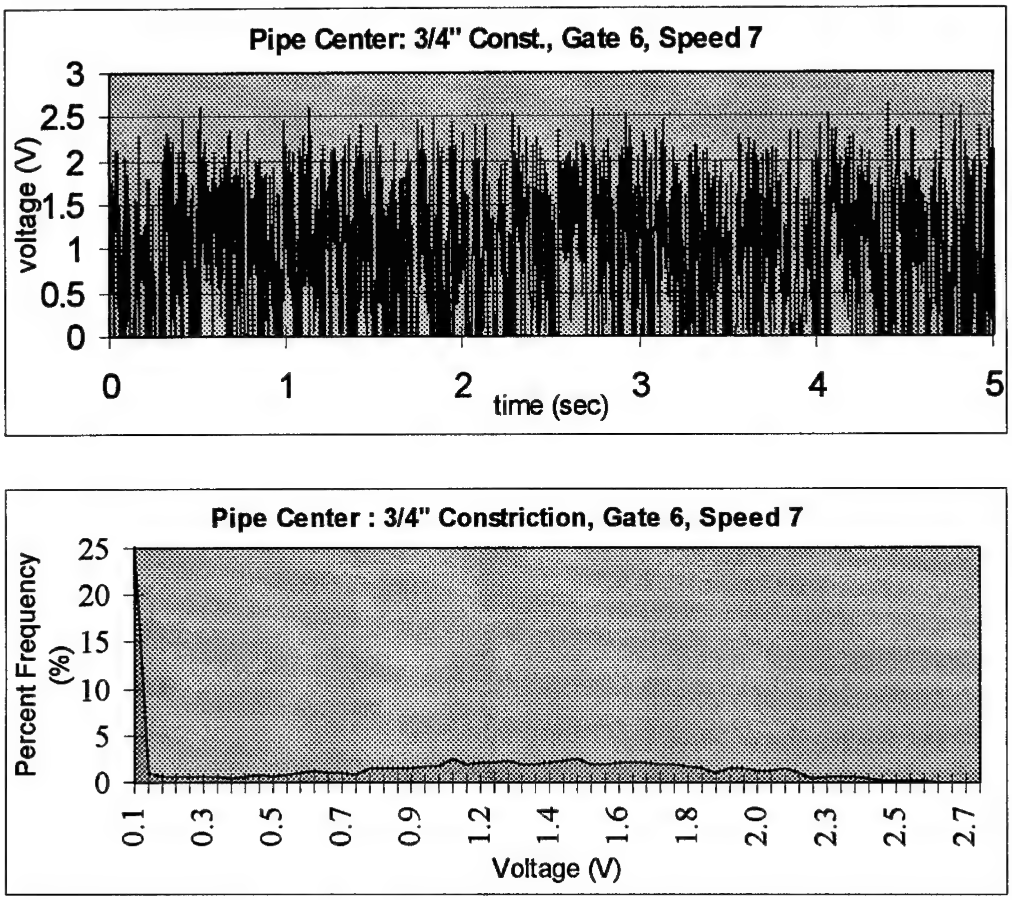


Figure 37: Test Sample of Wispy Air-Cellulose Flow

In this test, the measured voltage varied widely from 0V to about 2.5V. Conglomerations of cellulose were present, which is evident by the high percentage near zero volts in the histogram. However, these conglomerations were not large slugs which occupied the entire diameter of the pipe. No large air separations are present in the

graph. In slug flow, large air "pockets" would separate the slugs. Rather, these conglomerations of cellulose were smaller, light clusters of cellulose which would momentarily obstruct the laser. Additionally, a fairly even dispersion of air and cellulose was present in the flow as well, which is evident by the normal distribution curve in the center of the histogram. This would be classified as a "wispy" flow in which some light clusters of cellulose formed and traveled with the finer, more evenly dispersed cellulose and did not form into large slugs occupying the entire pipe diameter.

Figure 38 shows a contrasting test in which the air and cellulose were highly segregated during flow. Figure 38 shows a test sample from the bottom of pipe with a 5/8" constriction orifice, gate 6, blower speed 1. In this case, cellulose mass fraction was approximately 80%.

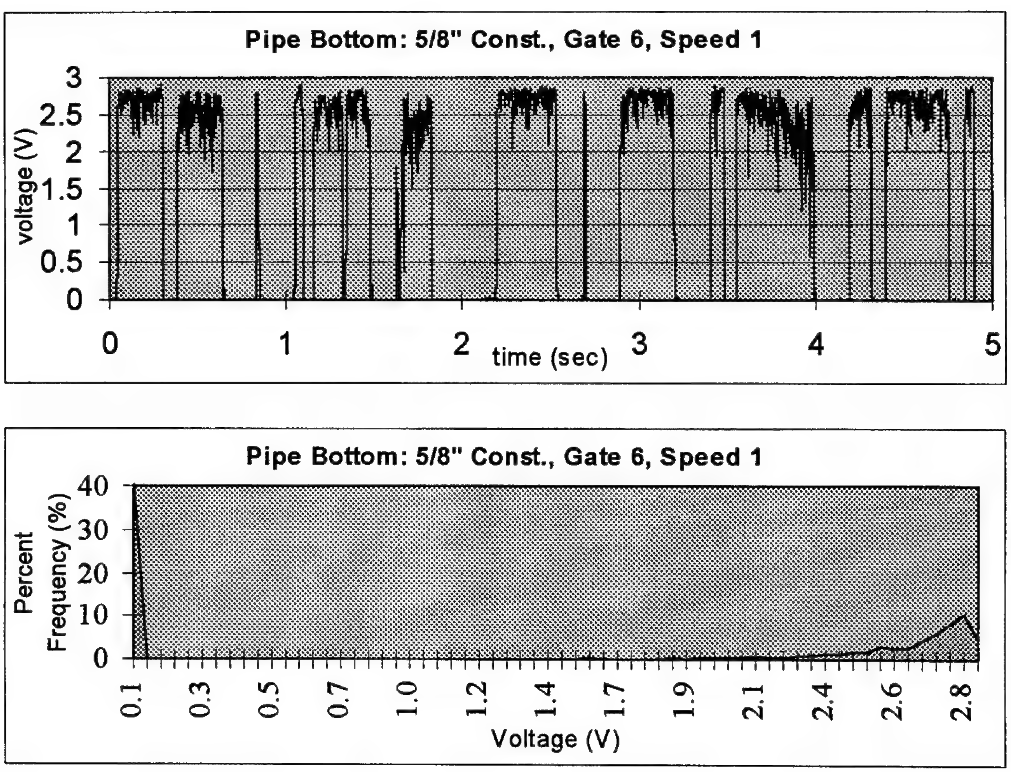


Figure 38: Test Sample of Segregated Air-Cellulose Mixture

In this test, the measured voltages range from 0 to almost 3 volts. The cellulose was not evenly dispersed in the airflow. The voltage vs. time graph shows how large slugs of cellulose passed through the laser beam blocking out the energy (0 V), followed by fairly clean pockets of air (≈ 3 V). The histogram shows the high percentages near 0 V and 3 V with very few voltage measurements in between. The varying lengths of time that the voltage was at zero shows the slugs passed through in varying sizes separated by varying volumes of air.

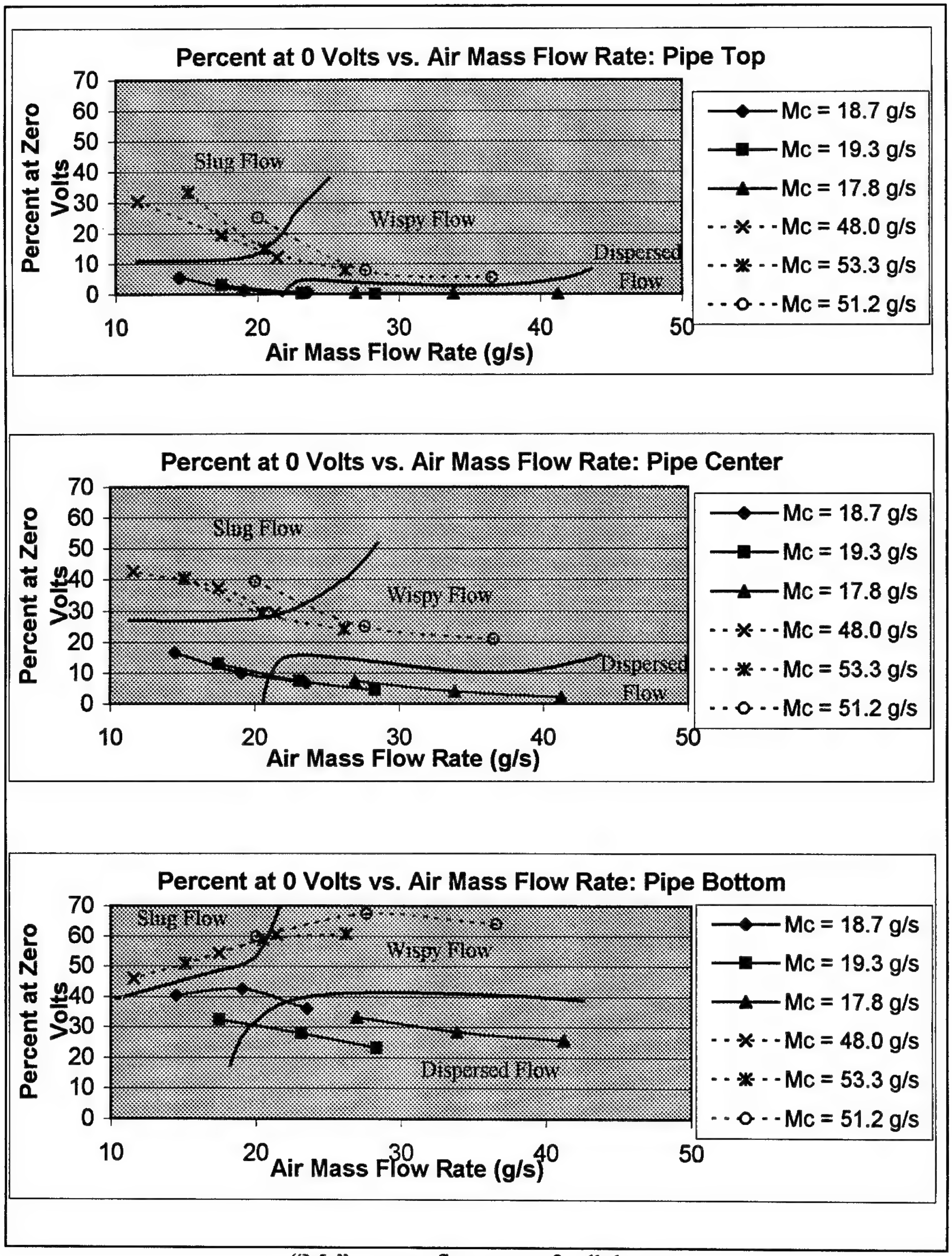
Appendix E contains 36 histograms from test samples for each test showing differences between dispersions at the top, center, and bottom of the pipe. They are arranged by increasing cellulose mass fractions. These histograms provide evidence of stratification in the pipe. The results exhibit indications of more evenly dispersed flow at the top of the pipe with the bottom of the pipe showing indications of slug flow. In general, clusters of cellulose would tend to follow the bottom of the pipe and become stratified from air and finer particles of cellulose at the top of the pipe. In all cases tested, some cellulose tended to conglomerate at the bottom of the pipe.

Figure 39 shows percent at zero values for at the top, middle, and bottom of the pipe. By observing the results for percent at zero volts for the top and center of the pipe, it can be seen that the percent at zero volts increased significantly with higher cellulose mass flow rates. The results show that the higher cellulose mass fractions tended to have significantly higher percents at zero volts, meaning that dense slugs of cellulose blocked the laser energy completely a higher percentage of the time. Increases in air mass flow rate tended to decrease the percent at zero volts, because the presence of more air in the

mixture lead to larger air spaces between slugs of cellulose. The higher amount of air separations would allow laser energy to pass through more often and decrease the percent at zero volts in most cases. Higher air flow rates also led to a more uniform dispersion of cellulose in the air. The air pockets had additional suspended material, which resulted in a lower average voltage.

Regimes of slug flow, wispy flow, and dispersed flow are marked on Figure 39, based on cellulose mass fractions. According to the laser histograms, air-cellulose flow with cellulose mass fractions below 45% had normal distributions at the center and top of the pipe. These would be generally be considered dispersed flows. None of the cases display completely uniform dispersal of cellulose in air, since a small amount of cellulose always clusters together and travels along the bottom of the pipe. Slug flow characteristics occurred at cellulose mass fractions above 70%. In the associated histograms, most of the measured voltages were at 0 volts or 3 volts through the entire cross section of the pipe. This indicated that slugs were traveling through the entire diameter of the pipe. Wispy flow generally falls between 45% and 70% cellulose mass fraction. It is the transition zone between slug flow and dispersed flow.

Additionally, observing the differences between the top, center, and bottom of the pipe, it can be seen that percent at zero volts was generally much higher at the bottom of the pipe than the top of the pipe. This would suggest that these slugs of cellulose are heavily influenced by gravity and tend to follow along the bottom of the pipe.



"Mc" = mass flow rate of cellulose

Figure 39: Percent at Zero Volts vs. Air Mass Flow Rate for Mixture Dispersion Testing

Tests with high mass fractions of cellulose above 70% show slug flow characteristics along the entire cross section of the pipe, caused by slugs filling the entire pipe diameter. The frequency of these slugs is of great concern, since it is not clear if they are natural, self-induced occurrences or if they are caused by the discrete injection of cellulose through the airlock of the fiber moving machine. In order to determine the frequency of these slugs, a Fast Fourier Transform (FFT) of the voltage outputs was performed for all the samples displaying characteristics of slug flow, with slugs occupying the entire diameter of the pipe separated by air pockets. From the FFT, the dominant frequency or frequencies of cellulose slugs could be determined. The points with the greatest amplitudes would indicate the dominant associated frequencies.

First, a frequency analysis was conducted on the flow moving directly out of the fiber moving machine **without** going through 60ft of tubing. In these tests, the samples were taken 10 ft downstream of the outlet of the fiber moving machine. Voltage vs. time samples were obtained, recorded, and analyzed using a Fast Fourier Transform. Figure 40 shows the voltage vs. time graph for flow with a cellulose mass fraction of approximately 72%.

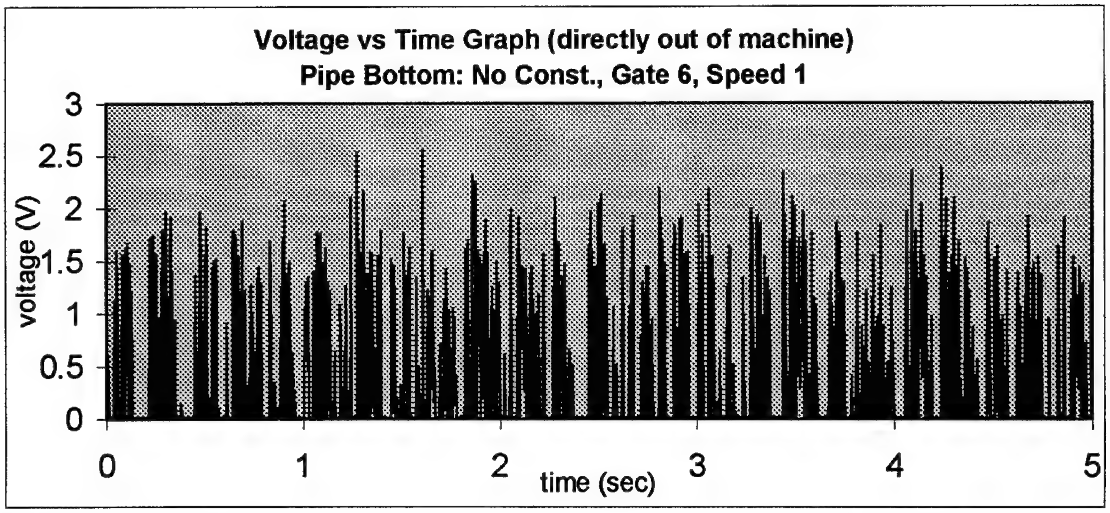


Figure 40: Voltage vs Time Graph Flow Directly Out of the Fiber Moving Machine with Cellulose Mass Fraction ≈ 72%

Figure 40 shows an obvious periodicity in the flow of cellulose. This periodicity is caused by the discrete injection of cellulose into the air stream through the airlock chambers. The FFT frequency analysis of this data verifies this periodicity in Figure 41. Figure 41 shows a clear amplitude spike occurring at 5.08 Hz, which represents the dominant frequency. This frequency is the same as the frequency of the rotating airlock chambers, as was described in section 7.2 on the Fiber Moving Machine. For lower cellulose mass fractions, the same results occurred.

Figures 42 and 43 show the voltage vs. time graphs for flow with cellulose mass fraction ≈ 58% and the respective frequency analysis. Figures 42 and 43 show the same dominant frequency of 5.08 Hz with some harmonic frequencies at 7.42 Hz and 10.16 Hz. The discrete airlock injection of cellulose clearly affects the flow patterns of cellulose coming directly out of the machine.

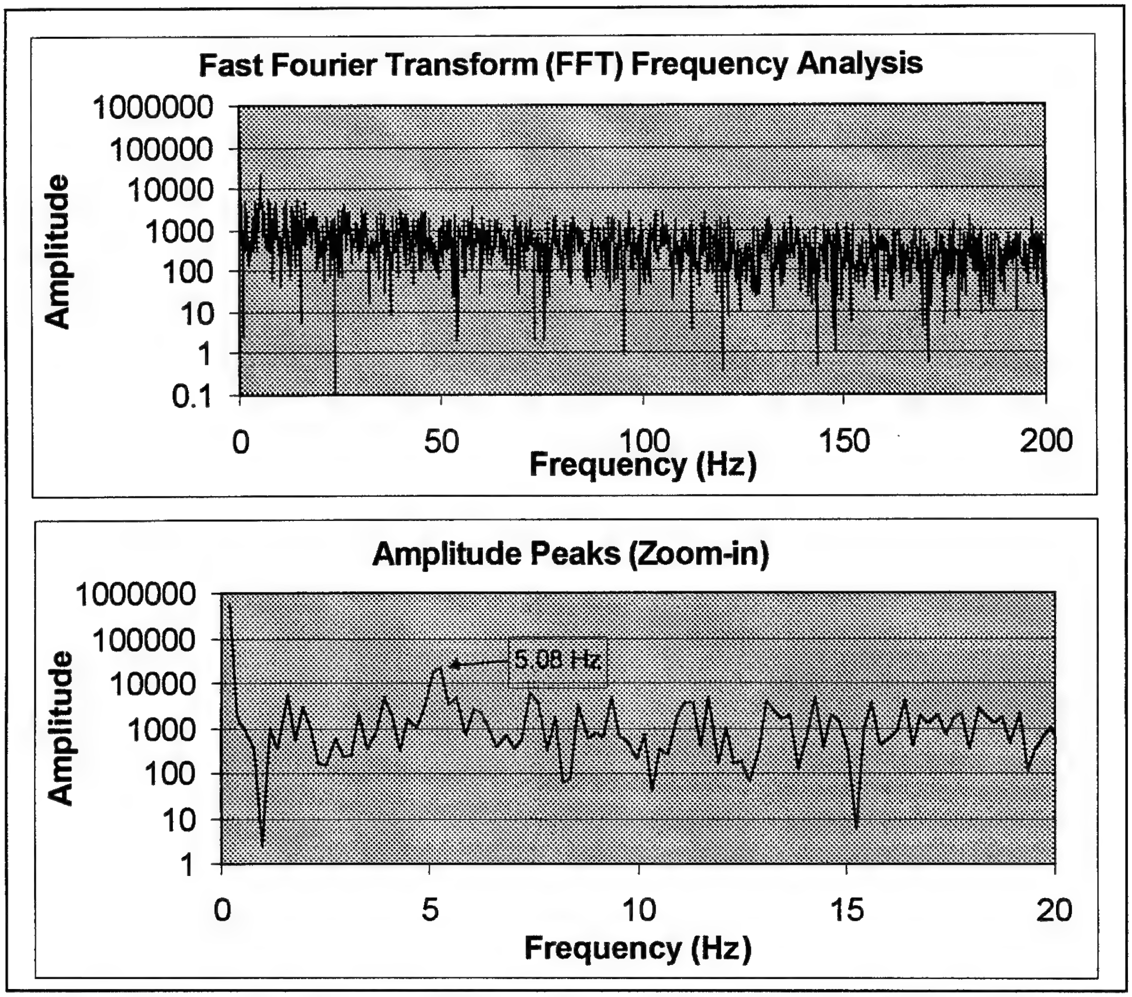


Figure 41: Frequency Analysis for Test Sample Directly out of the Fiber Moving Machine with Cellulose Mass Fraction ≈ 72%

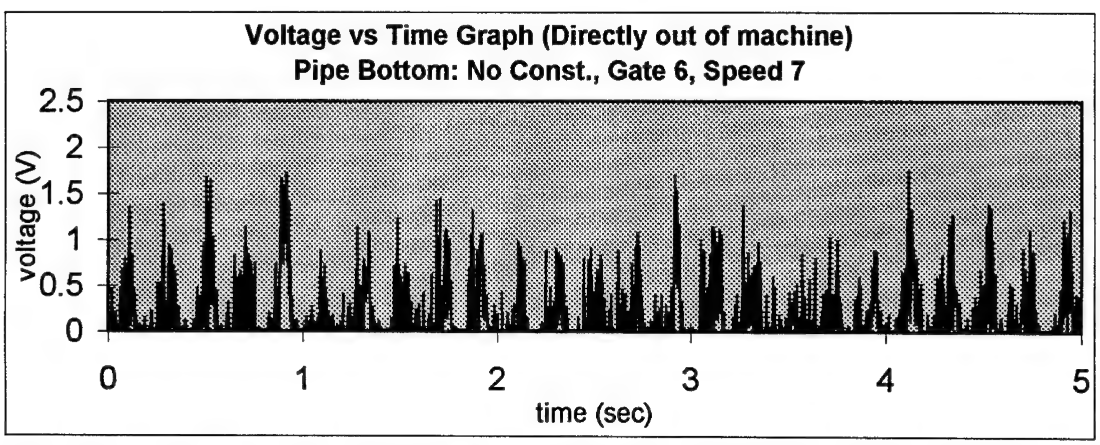


Figure 42: Voltage vs. Time Graph Flow Directly Out of the Fiber Moving Machine with Cellulose Mass Fraction ≈ 58%

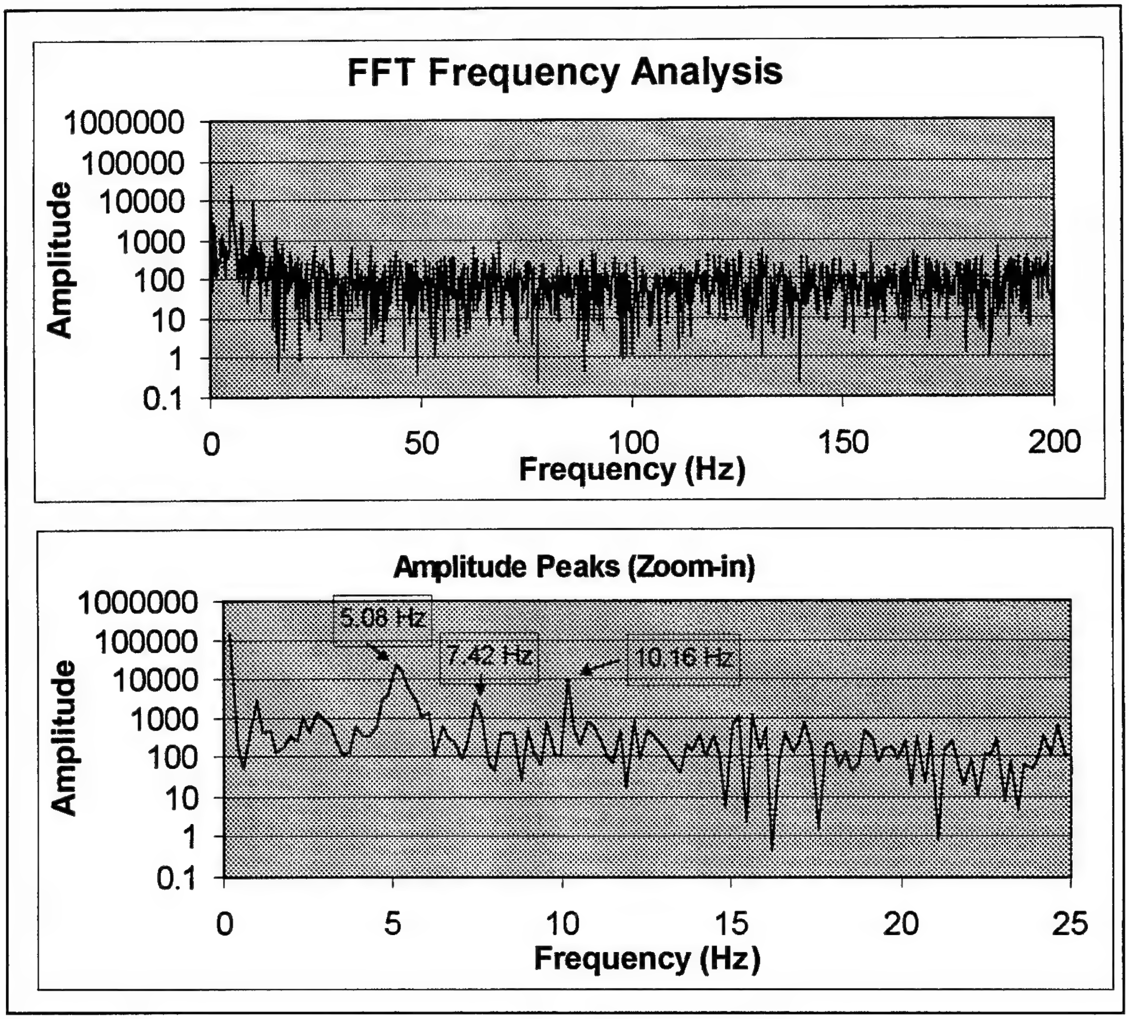


Figure 43: Frequency Analysis for Test Sample Directly out of the Fiber Moving Machine with Cellulose Mass Fraction ≈ 72%

The results of the FFT analysis for flow moving directly out of the machine was compared to slug flow after moving through 60 ft of rough tubing. Figure 40 shows the results of the FFT analysis for the sampling conducted with the 5/8" constriction, gate 6, blower speed 7, with a cellulose mass fraction of 80%, after 60ft of tubing. The original voltage vs. time graph for this sample appears in Figure 38.

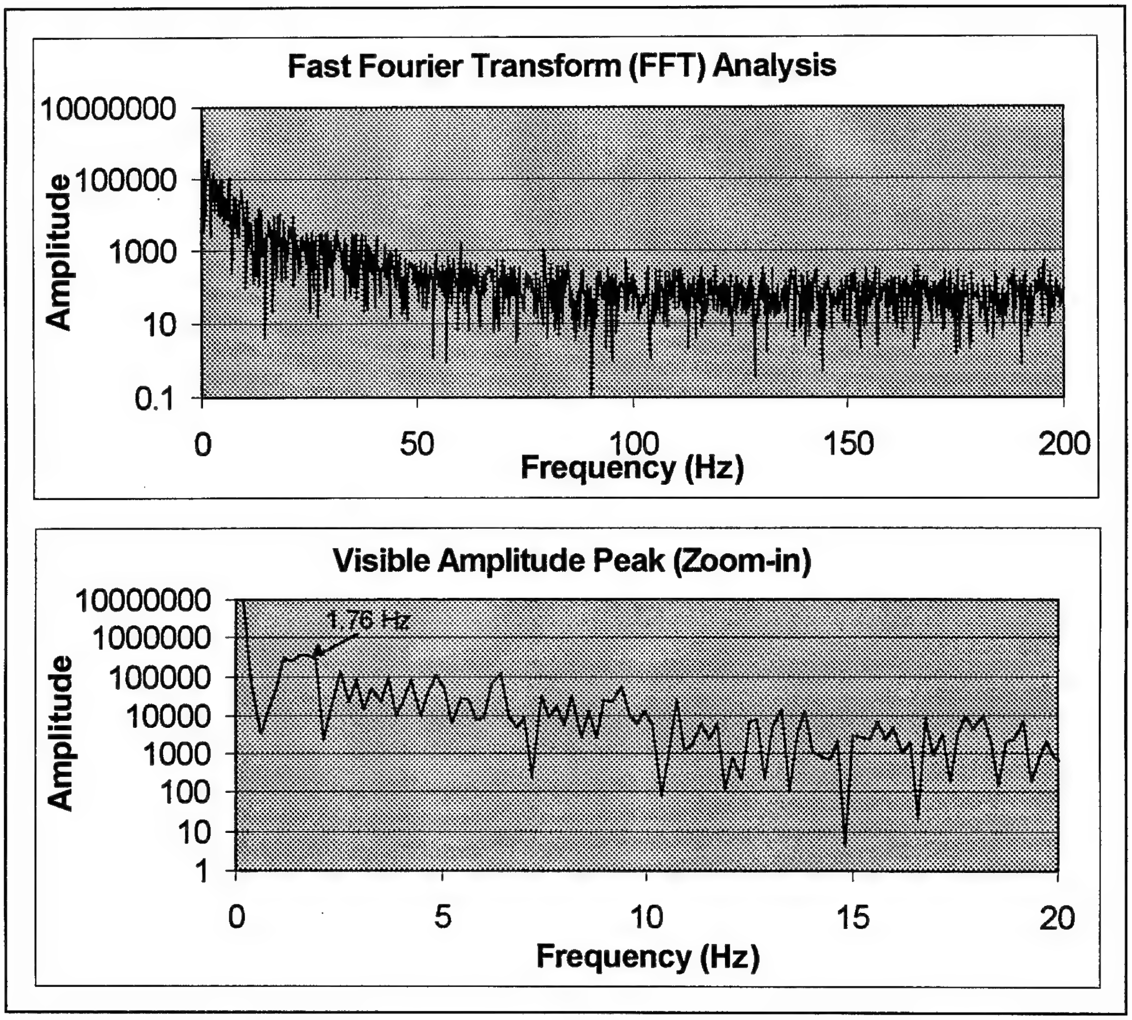


Figure 44: Frequency Analysis for Test Sample with Cellulose Mass Fraction ≈ 80%

The FFT graphs in Figure 44 do not show clear amplitude spikes which would be indicative of a clearly dominant slug frequency. Rather, there is a faint, indistinct peak which appears at about 1.76 Hz with a number of other peaks in close proximity. These other frequencies would indicate harmonics which also make up the overall frequency spectrum of the slugs. Since the slugs did not occur in exact intervals with exact air separations, this wide spectrum of frequencies is expected. The dominant frequency of 1.76 Hz equals a period of 0.57 sec per slug which validly portrays the average period of

the slugs as seen in Figure 38 on the voltage vs. time graph. There is a wide variation above and below this period.

The tests conducted for flow with cellulose mass fractions of 80% were the only tests that had even a faintly dominant frequency associated with the cellulose slugs. The next greatest cellulose mass fraction tested was 77% with a ¾" constriction at gate 6, blower speed 1 (see Table 4). Figure 45 shows the original voltage vs. time graph sample and Figure 46 shows the frequency analysis for that sample.

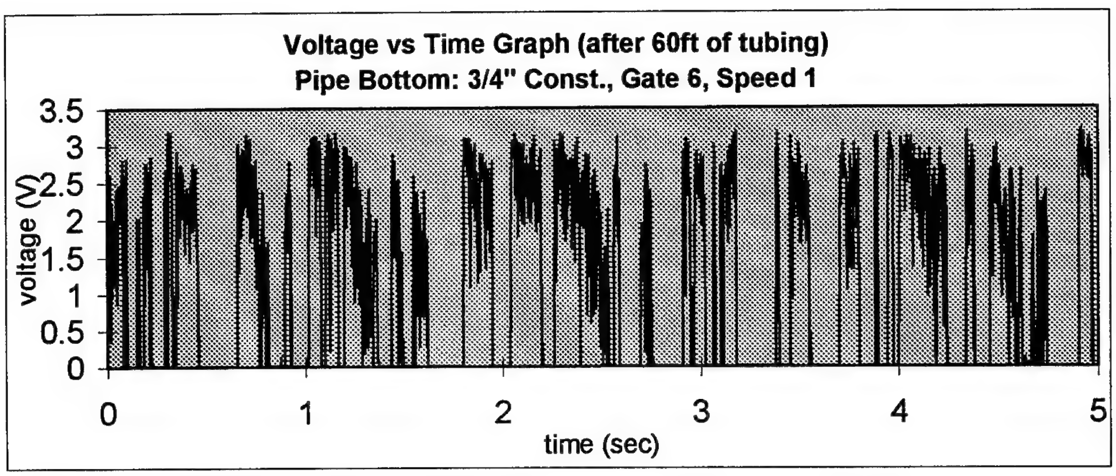


Figure 45: Voltage vs. Time Graph for Cellulose Mass Fraction ≈ 77%

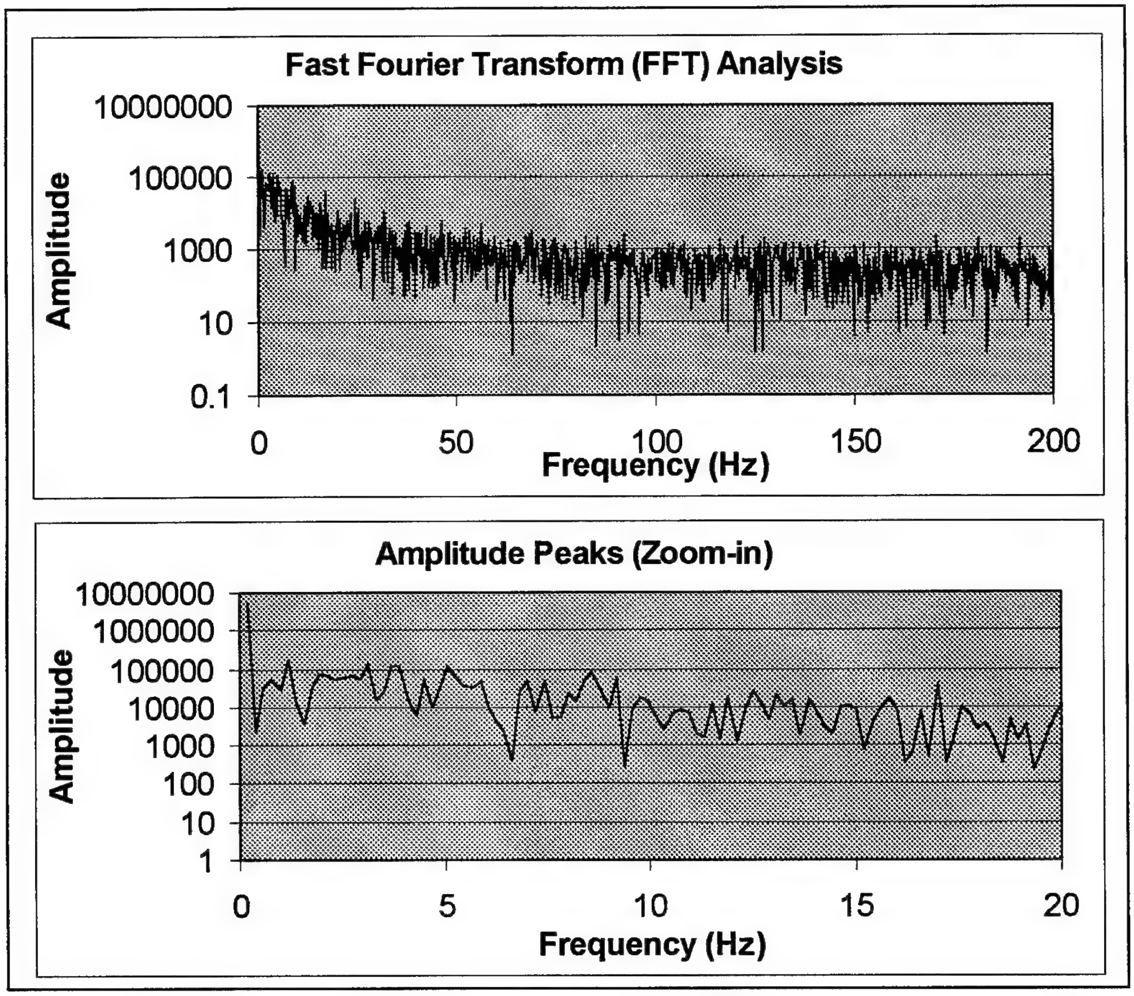


Figure 46: Frequency Analysis for Test Sample with Cellulose Mass Fraction ≈ 77%

The results in Figure 46 show that there was no clearly dominant frequency associated with this flow. Rather, there were a number of harmonic frequencies with comparable amplitudes ranging from 1 Hz to 10 Hz. Visual examination of Figure 45 tends to verify these results since there does not seem to be any clear frequency associated with the presence of slugs. The bursts are fairly random in length and interval. For cellulose mass fractions below 77%, this pattern continued. With lower mass

fractions, the voltage fluctuations were less pronounced and frequencies of slugs were not apparent.

The results of the measurements and analyses made after the cellulose flows through 60ft of rough tubing do not show a clearly dominant frequency at 5 Hz, as in the measurements conducted directly out of the machine. However, the most dominant frequencies do tend to occur in the general area of 5 Hz, as is apparent in Figure 44 and 46. From this data, it can be inferred that the slugs of cellulose observed in the pipe at high cellulose mass fractions are likely to be natural and self-occurring, but may still be partially linked to the original cellulose injection process. While the slugs do not have clearly dominant frequencies at exactly 5 Hz, the numerous harmonic frequencies do tend to fall in the same area. In general, the slugs have a wide variation of length and interval without a very specific periodicity like the clusters of cellulose coming directly out of the machine.

With small cellulose mass fractions, some cellulose traveled interlocked together in thin clusters flowing along the bottom of the pipe. Other fine cellulose fibers were dispersed evenly throughout the center and top of the pipe. With increasing cellulose mass fractions, the size of these slugs increased. In the large cellulose mass fractions tested above 70%, the cellulose would form into long, dense slugs occupying the entire diameter of the pipe. The slugs would be separated by volumes of clean air which did not contain fine, evenly dispersed cellulose fibers.

These results provide evidence that increasing the mass fractions of cellulose causes a move from a generally dispersed flow towards slug flow, in which cellulose entangles together in large, dense slugs. In most gas-solid mixtures, increases in solid

mass fractions cause the flow to move from an even dispersion to a stratified flow in which the solid forms on the bottom with the gas passing over it. However, in air-cellulose mixtures the interlocking nature of the cellulose causes the formation of large slugs with higher mass fractions, which fill the entire cross section of the pipe. Figure 47 displays the flow regimes associated with dispersed flow, wispy flow, and slug flow for this research, based on the experimental results.

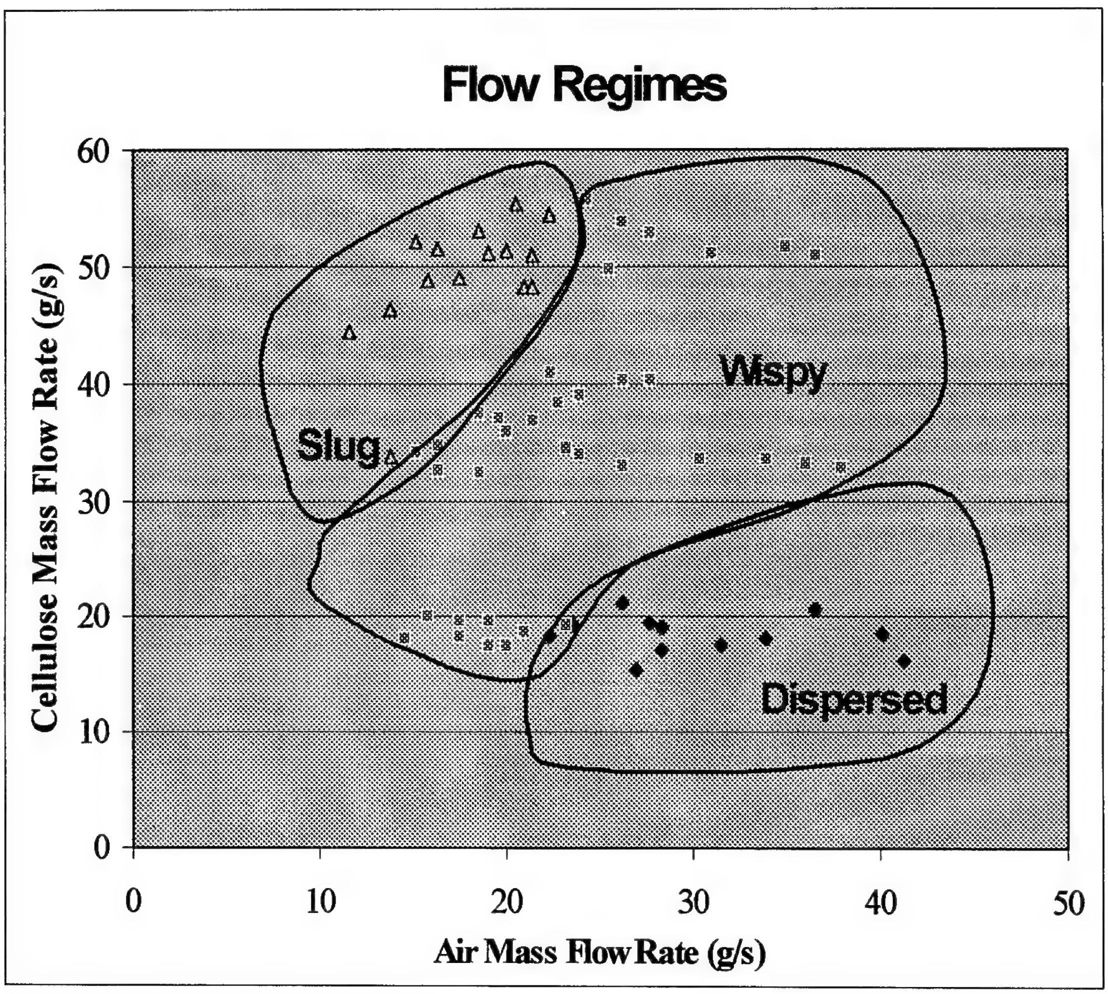


Figure 47: Flow Regimes

8.4 Correlation Between Mass Fraction, Pressure Gradient, and Mixture Dispersion Results

The results of pressure gradient testing have interesting correlations with the mass fraction and mixture dispersion results. Figure 30 showed the relation between the pressure gradient and air velocity of air-cellulose mixtures. In general air flow, the pressure drop tends to decrease with a decrease in air velocity. However, in the gas-solid mixture of air and cellulose, the pressure gradient tended to increase with decreases in air velocity when cellulose mass fractions were higher. Figure 48 shows pressure gradient versus velocity as earlier in Figure 30 with the cellulose mass fraction ranges indicated.

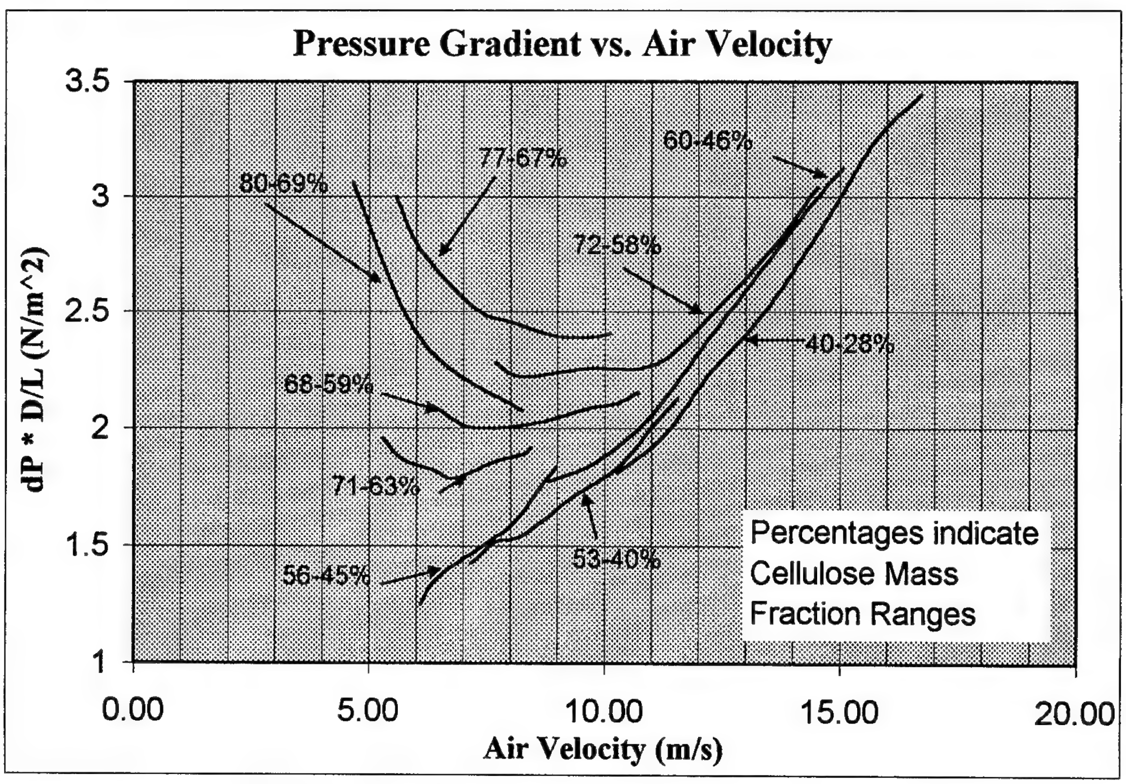


Figure 48: Cellulose Mass Fraction on Pressure Gradient Curves

Figure 48 displays the cellulose mass fraction ranges for each pressure gradient curve. The highest cellulose mass fraction in the range is always associated with the far left point on the curve while the lowest cellulose mass fraction is associated with the far right point on each curve. These results show that at cellulose mass fractions of 65%, the relationship between pressure gradient and air velocity begins to change. The pressure gradient is at its lowest point for each curve at about 65% mass fraction, for all the curves that reach that cellulose mass fraction. Above 65%, the pressure gradient tends to increase with decreases in velocity. Below 65%, the pressure gradient tends to increase with increases in velocity.

The results of mixture dispersion testing show that at above 60 to 65% cellulose mass fraction, the cellulose is forming into fairly large slugs flowing along the bottom of the pipe, as is evident by the histograms displayed in Appendix E. The change in relationship between pressure gradient and air velocity may be due to the presence of these large cellulose slugs. Figure 49 displays the cellulose mass fraction regimes associated with the pressure gradient vs. air velocity graph. Sample laser test histograms are also displayed to show the dispersion of cellulose for each mass fraction range.

In general, air-cellulose mixtures share similar flow characteristics as most gas-solid mixtures flowing in pipes. The greatest differences occur in the formations which occur at high solid mass fractions. In most gas-solid mixtures, a high solid mass fraction will cause the solid to become stratified from the air forming a bed on the bottom of the pipe with air moving above it. However, in air-cellulose mixtures solid slugs of cellulose form with high cellulose mass fractions.

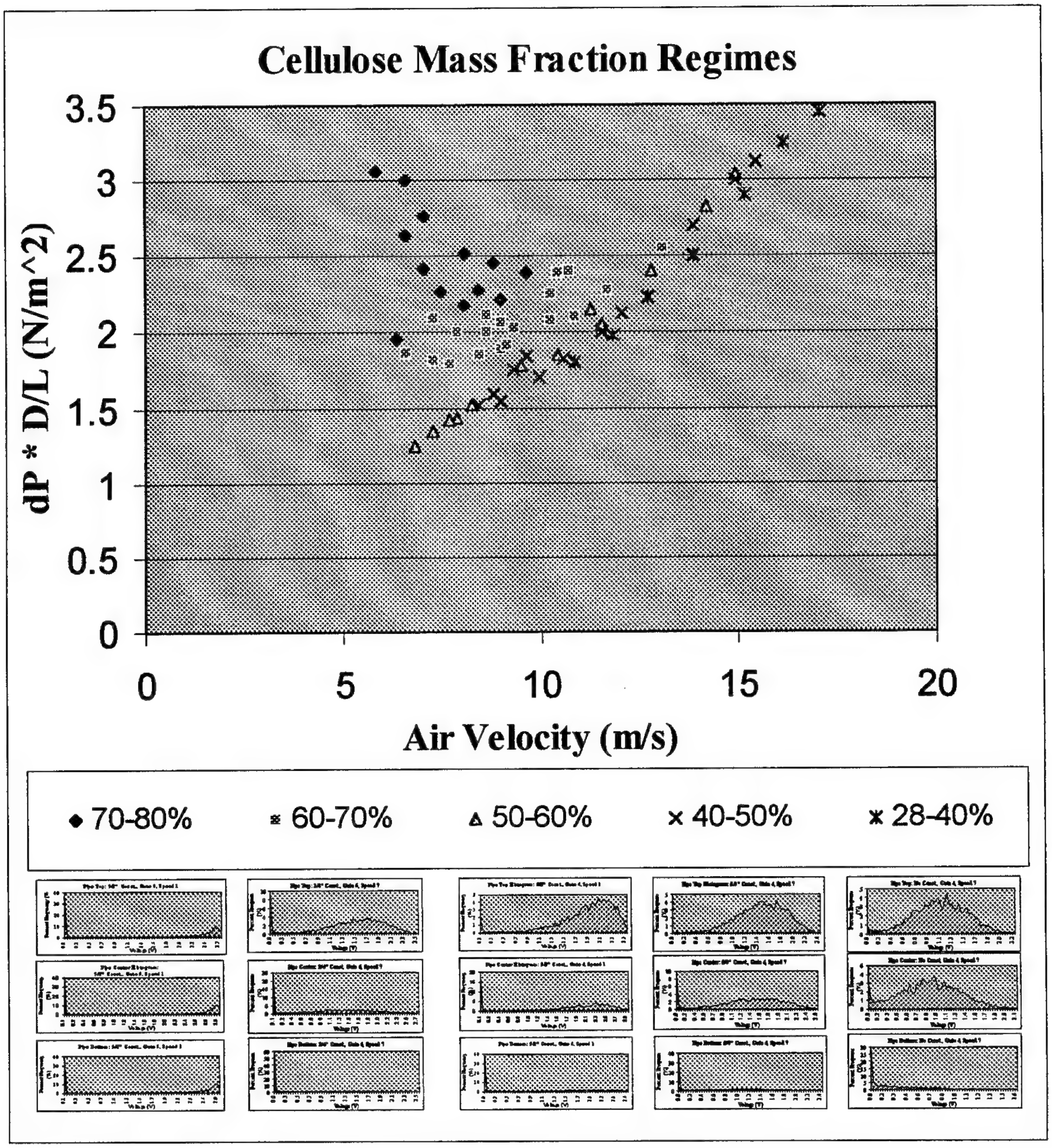


Figure 49: Cellulose Mass Fraction Regimes on Pressure Gradient vs. Velocity Graph

8.5 Contribution of Testing Results to Engineering Community

The pressure gradient information collected in this research can aid in determining energy requirements needed to move various mass fractions of cellulose at particular velocities. It also shows the relationship between mass fraction and pressure drop, as well as the general points at which the pressure drop is lowest under given flow conditions. In general, the pressure gradient results show the relationship between pressure drop and velocity for the flow of air-cellulose suspensions.

Results of the mixture dispersion testing display the physical flow characteristics of air and cellulose with different mass fractions. The dispersion histograms display how the flow transitions from fairly dispersed air-cellulose mixtures to highly segregated cellulose slugs separated by pockets of air. Using these results, flow regimes in air-cellulose flow were classified and related to specific cellulose mass fractions.

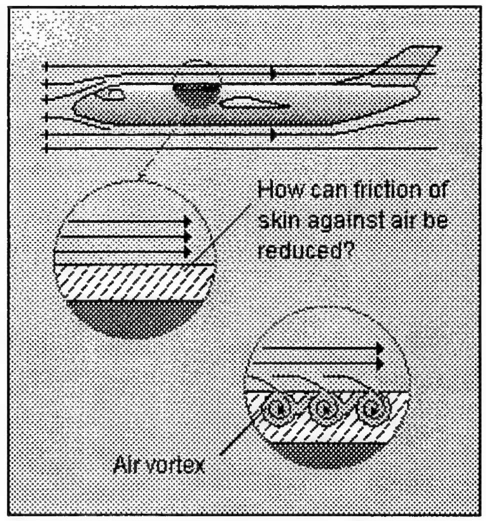
8.6 Future Research

Further research could be conducted to investigate the effects of pipe roughness on the pressure drops and flow patterns associated with air-cellulose pipe flow. Also, water could be added to the cellulose to analyze the effects of moisture on cellulose transport. Pipe size might play an important role in the formation of cellulose slugs. Research could be conducted to investigate the effects of pipe size on cellulose transport.

APPENDIX A: Example for principle 22 - 'Blessing in disguise'

[Developed from Invention Machine™ Software]

THE AIR LUBRICANT PARADOX



How can the friction of an airplane skin against air be reduced? First, what is friction? It is caused by air flow 'touching' the skin of the aircraft; in Aerodynamics this is known as skin friction drag.

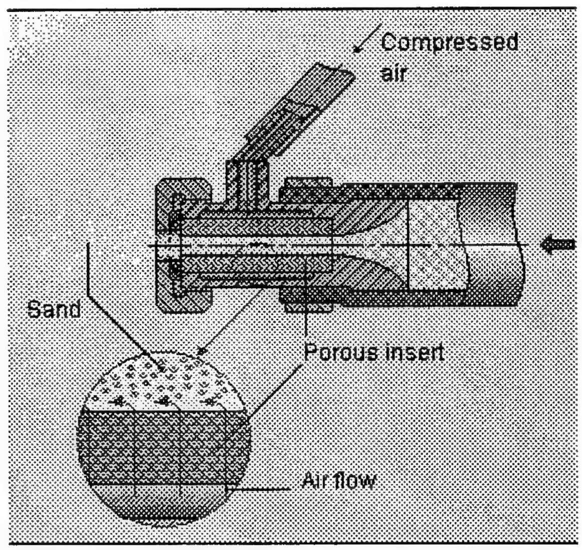
It is proposed to use the blessing in disguise principle to reduce skin friction. One can intensify the 'touching' to the extent that the air flow gets into the skin (a condition that would seem to increase the friction). For this to occur, the straight-line motion of the air along the skin must be changed into a rotary motion in the skin. Lateral cylindrical slots are formed in the skin that communicate with the atmosphere via narrow slits. On entering these, air is forced to rotate at a high speed forming vortex rings. These rings force approaching airflow away from the skin thereby serving as a kind of air lubricant, the blessing in disguise. The fabrication of this skin design, though, becomes much more complex.

APPENDIX B: Example of Porous Materials and Intermediary

[Developed from Invention Machine™ Software]

Concept #3
You may move cellulose to a wall using an intermediate carrier article or intermediate process.
You may move cellulose to a wall using porous materials

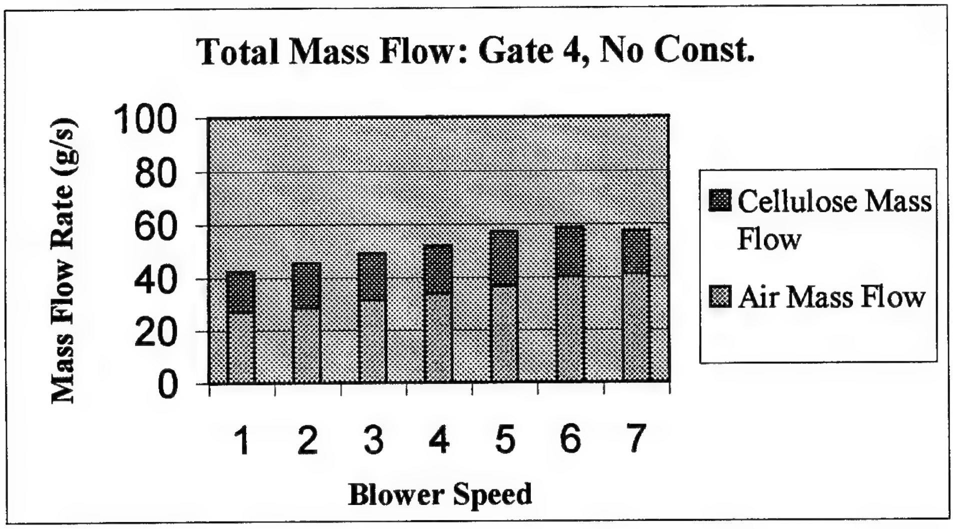
Example for principle 31 - Porous materials AND principle 24 - Intermediary
SAND BLASTER NOZZLE

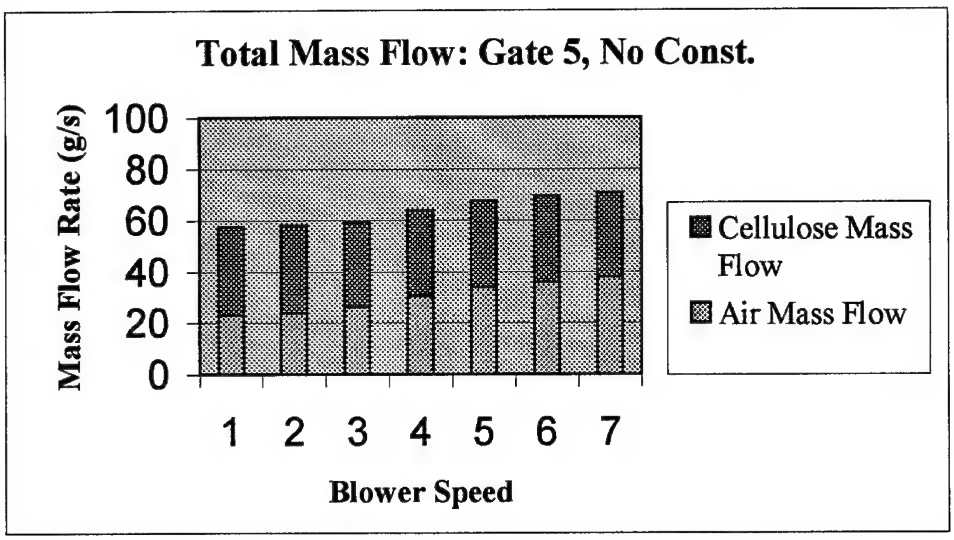


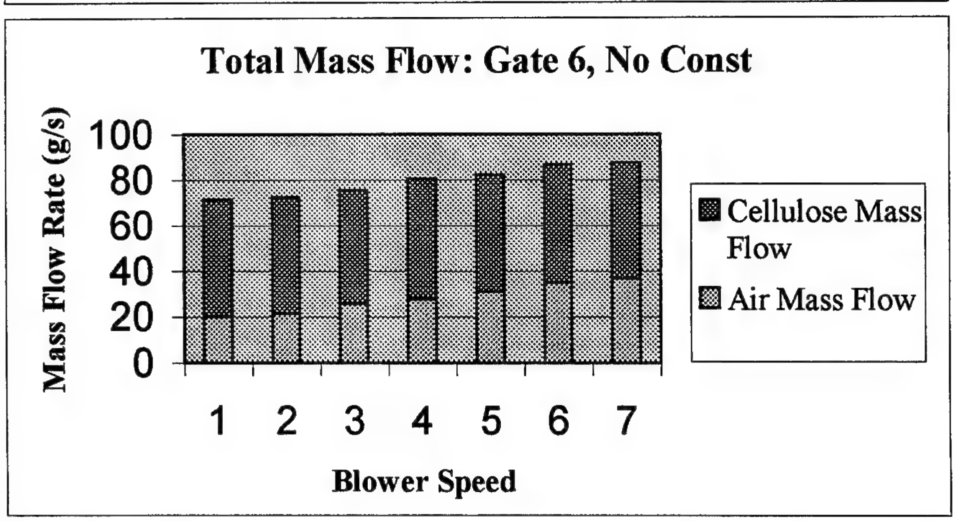
How can the wear of a sand blaster body insert be reduced?

It is proposed to use the principles of pneumatic and hydraulic constructions, porous materials and an intermediary to reduce the wear. One can make the insert from a porous material forming an annular passage in the body. Compressed air is forced through pores in the insert. During sand blaster operation, the compressed air forms a protective boundary layer at the insert inner surface. Sand passing through the nozzle tends to glide over this layer without touching the insert wall. This results in a longer service.

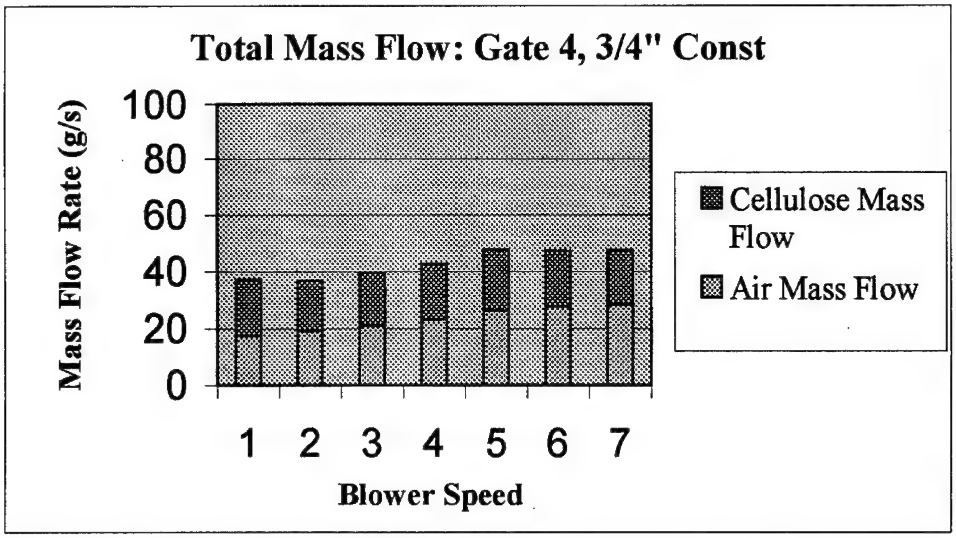
APPENDIX C-1: Total Mass Flow Bar Graphs

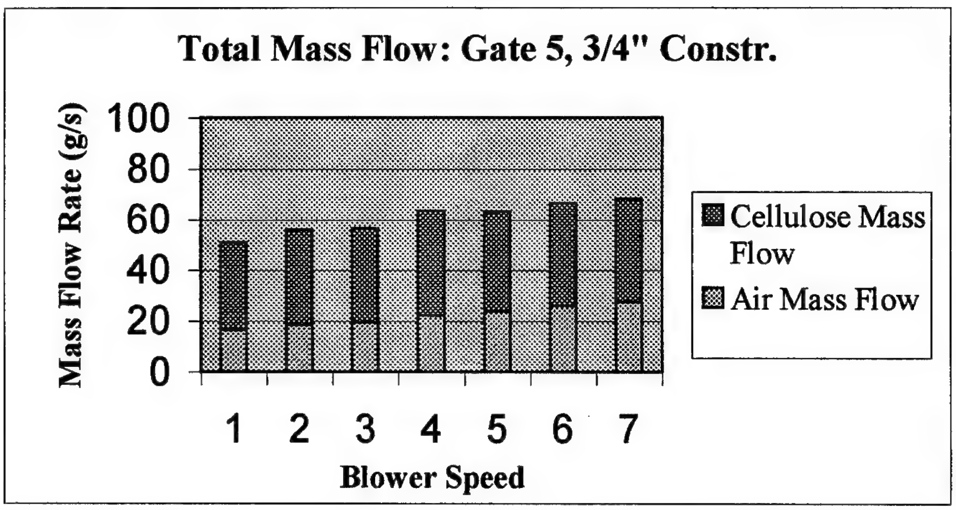


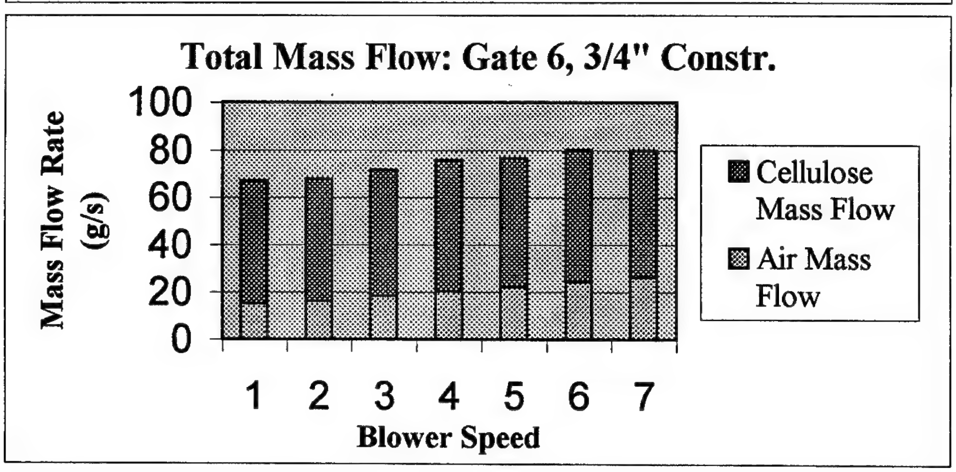




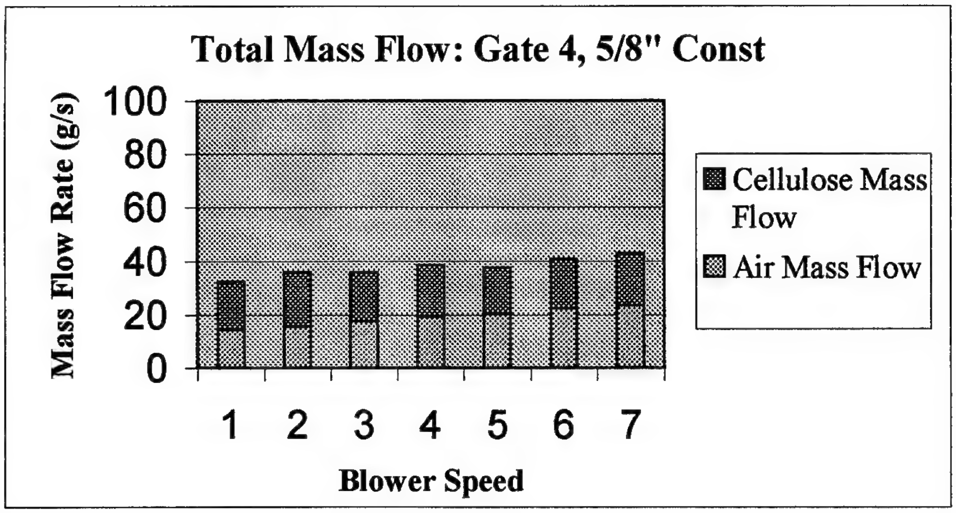
APPENDIX C-2: Total Mass Flow Bar Graphs

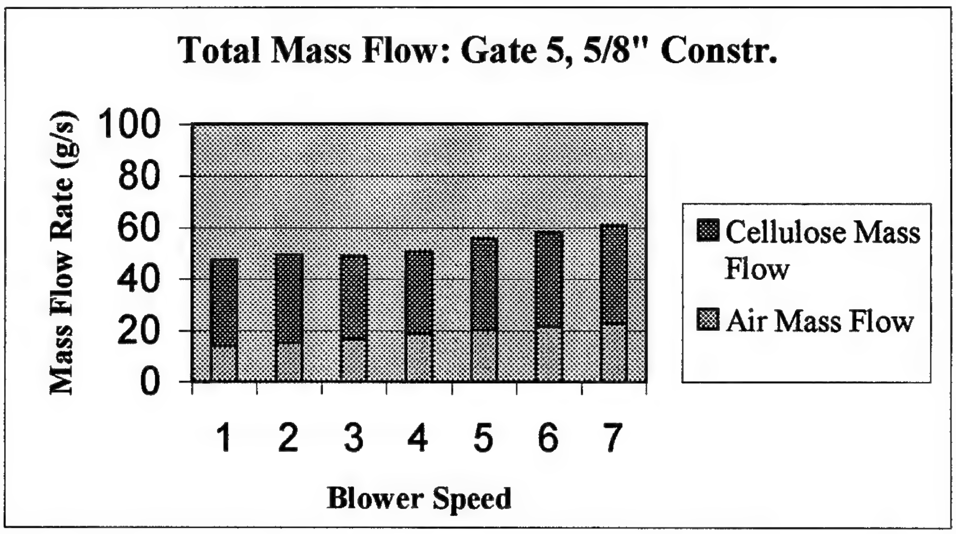


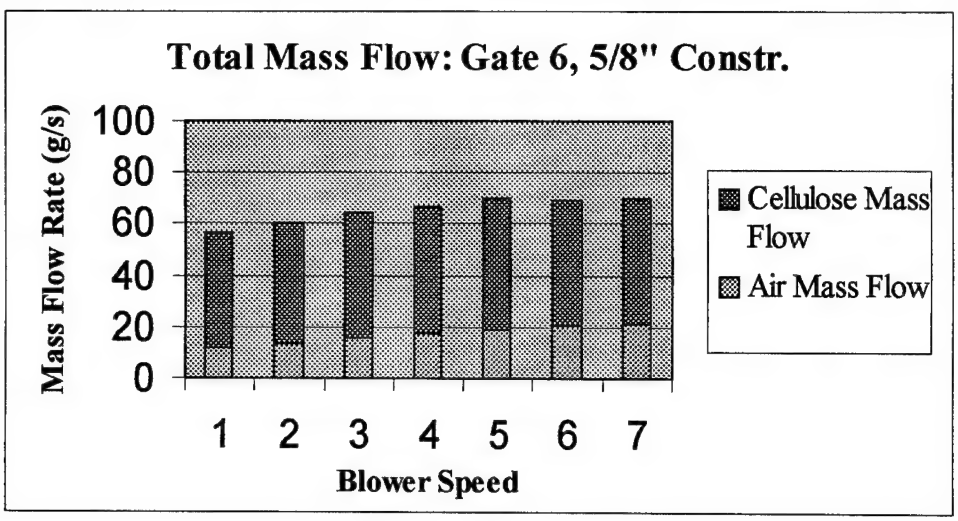




APPENDIX C-3: Total Mass Flow Bar Graphs







APPENDIX D-1: Tabulated Results of Mixture Dispersion Laser Testing

PIPE TOP				
Gate Setting	Constriction Size	Blower Speed	Average Voltage (volts)	Percent at Zero Volts (%)
4	5/8"	7	1.50	0.7
4	5/8"	4	1.67	1.4
4	5/8"	1	1.84	5.4
6	5/8"	7	1.60	12.1
6	5/8"	4	1.69	19.4
6	5/8"	1	1.91	30.6
4	3/4"	7	1.45	0.1
4	3/4"	4	1.54	0.4
4	3/4"	1	1.74	2.9
6	3/4"	7	1.45	8.0
6	3/4"	4	1.64	15.1
6	3/4"	1	1.90	33.5
4	none	7	1.21	0.2
4	none	4	1.35	0.2
4	none	1	1.57	0.5
6	none	7	1.39	5.5
6	none	4	1.53	7.8
6	none	1	1.82	25.0

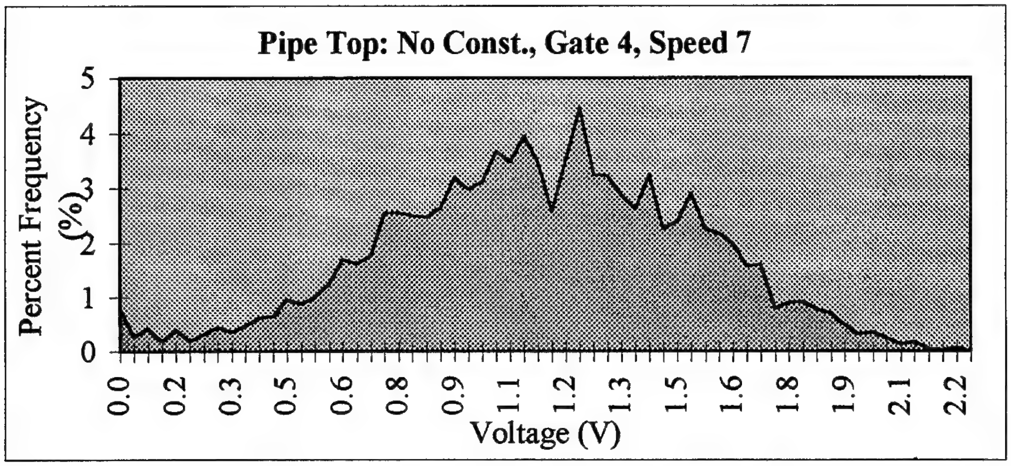
APPENDIX D-2: Tabulated Results of Mixture Dispersion Laser Testing

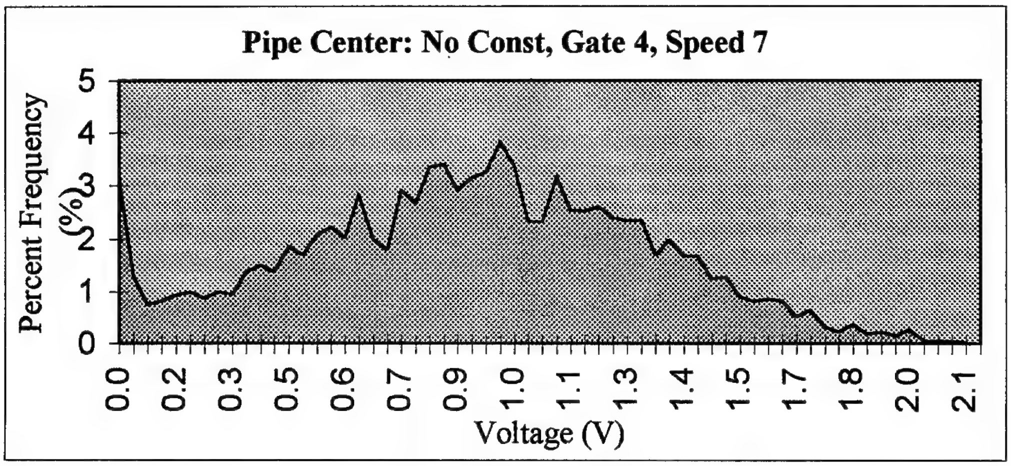
PIPE CENTER				
Gate Setting	Constriction Size	Blower Speed	Average Voltage (volts)	Percent at Zero Volts (%)
4	5/8"	7	1.49	6.9
4	5/8"	4	1.67	9.9
4	5/8"	1	1.88	16.6
6	5/8"	7	1.50	29.4
6	5/8"	4	1.70	37.4
6	5/8"	1	2.01	42.8
4	3/4"	7	1.13	4.4
4	3/4"	4	1.37	7.4
4	3/4"	1	1.65	12.9
6	3/4"	7	1.19	24.1
6	3/4"	4	1.45	29.2
6	3/4"	1	1.79	40.5
4	none	7	0.88	2.1
4	none	4	1.08	4.0
4	none	1	1.36	7.3
6	none	7	0.91	21.1
6	none	4	1.21	25.0
6	none	1	1.59	39.3

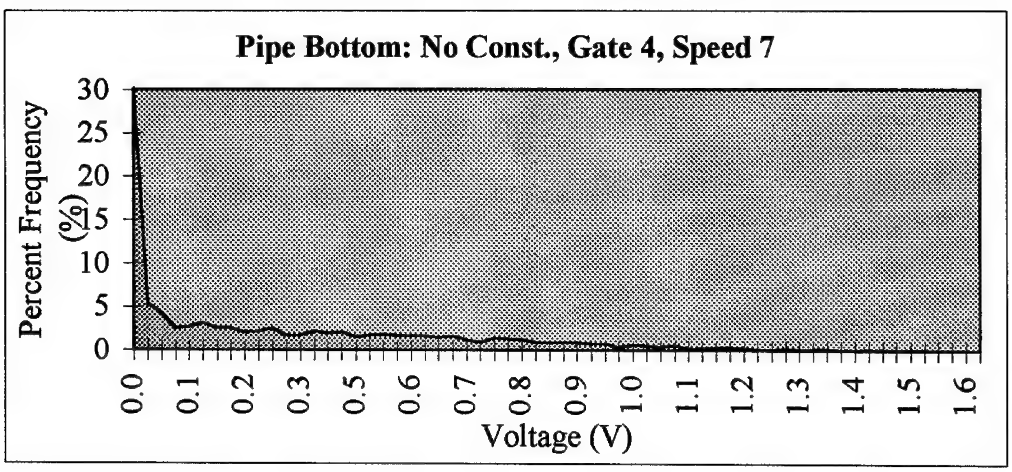
APPENDIX D-3: Tabulated Results of Mixture Dispersion Laser Testing

PIPE BOTTOM				
Gate Setting	Constriction Size	Blower Speed	Average Voltage (volts)	Percent at Zero Volts (volts)
4	5/8"	7	0.88	36.1
4	5/8"	4	1.08	42.6
4	5/8"	1	1.28	40.4
6	5/8"	7	0.94	60.4
6	5/8"	4	1.18	54.3
6	5/8"	1	1.94	46.0
4	3/4"	7	0.86	23.2
4	3/4"	4	1.02	27.9
4	3/4"	1	1.28	32.3
6	3/4"	7	0.79	60.6
6	3/4"	4	1.15	58.8
6	3/4"	1	1.79	51.0
4	none	7	0.41	25.6
4	none	4	0.55	28.4
4	none	1	0.83	33.3
6	none	7	0.46	63.9
6	none	4	0.62	67.4
6	none	1	1.13	59.7

APPENDIX E-1: Mixture Dispersion Laser Test Histograms

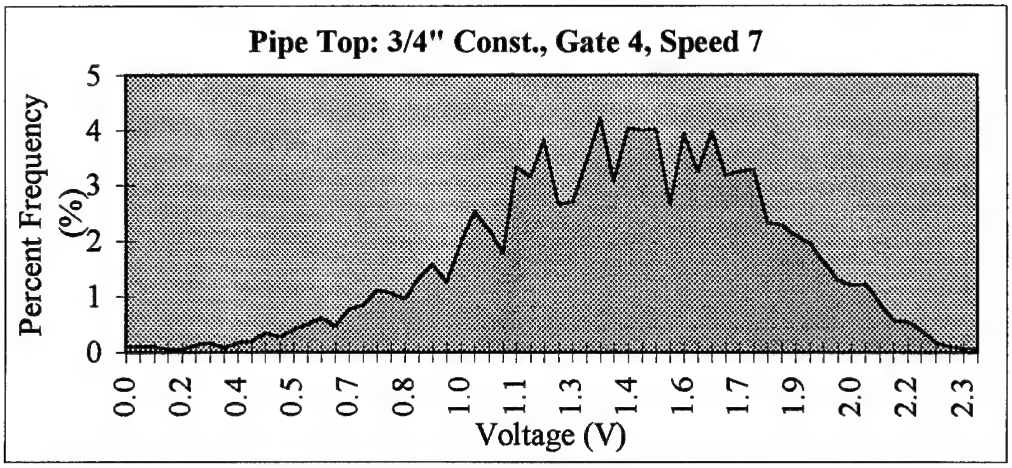


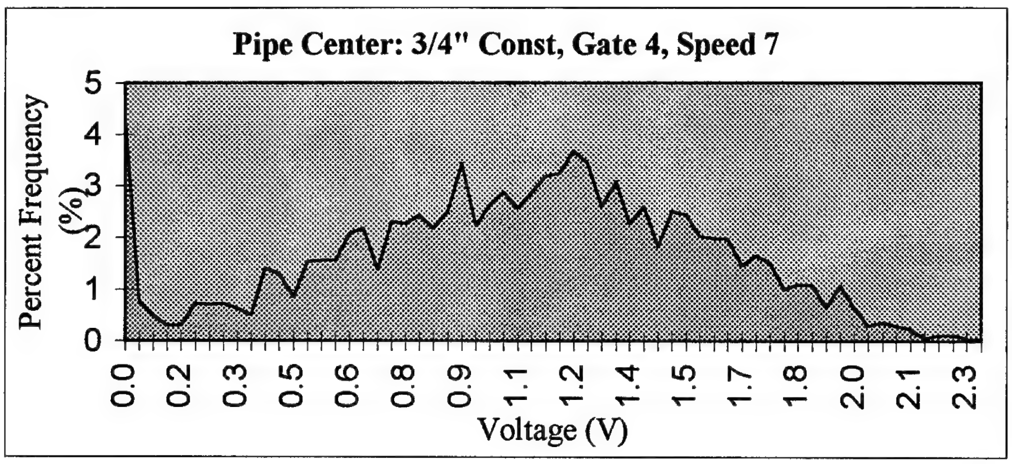


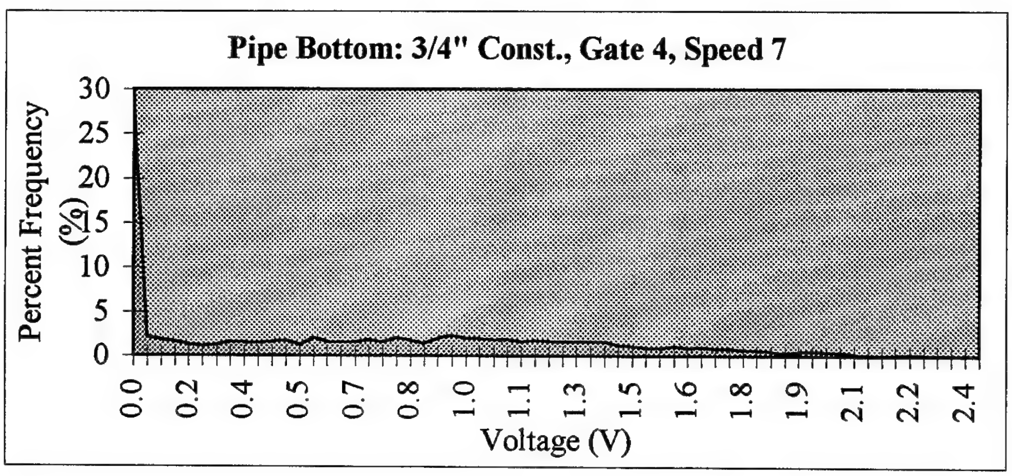


Cellulose Mass Fraction ≈ 28%

APPENDIX E-2: Mixture Dispersion Laser Test Histograms

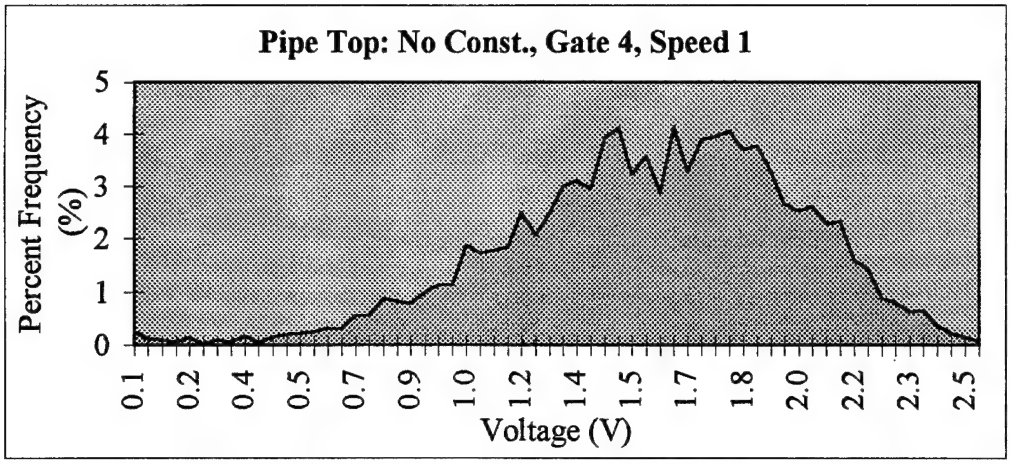


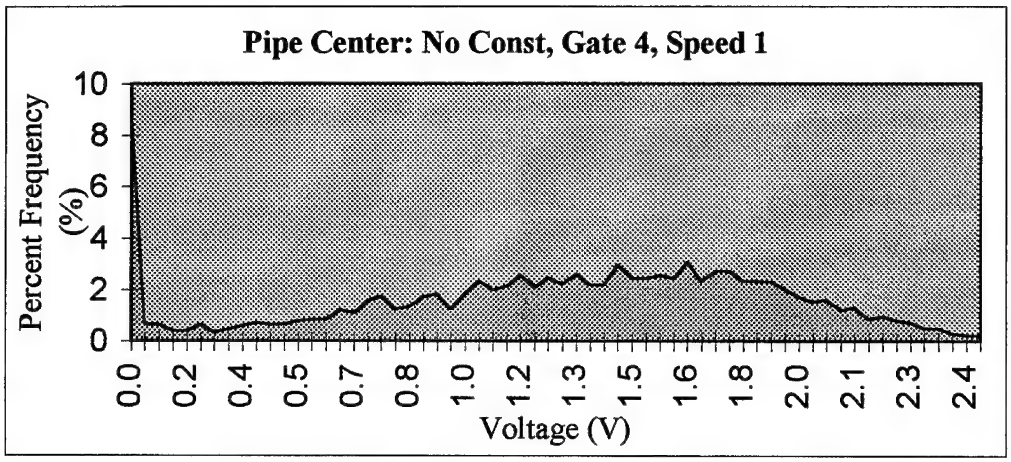


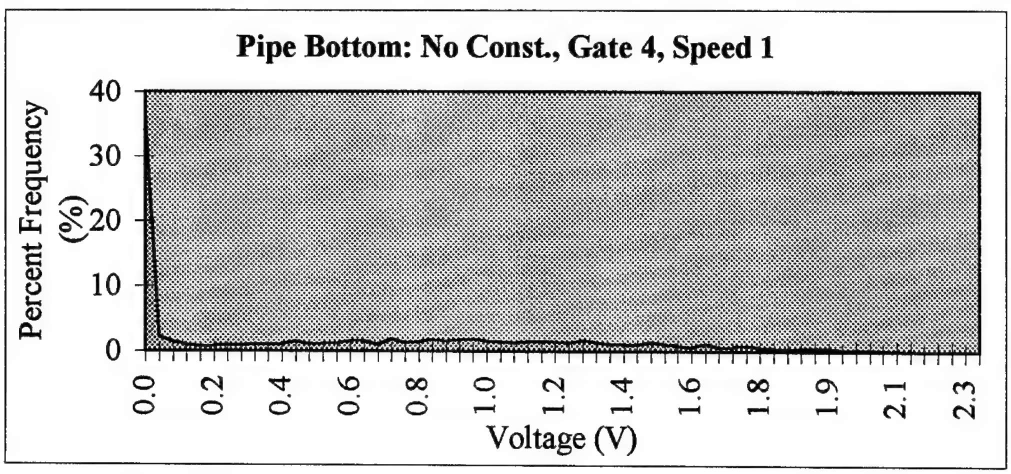


Cellulose Mass Fraction ≈ 40 %

APPENDIX E-3: Mixture Dispersion Laser Test Histograms

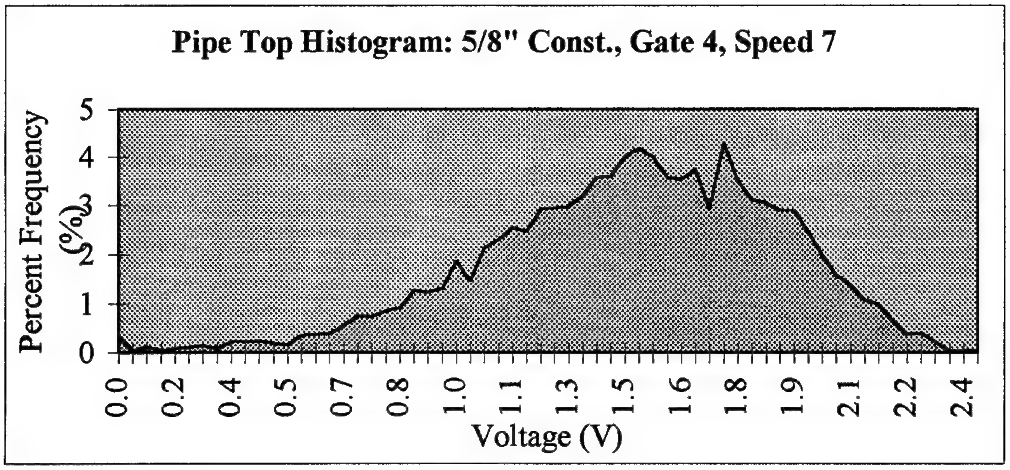


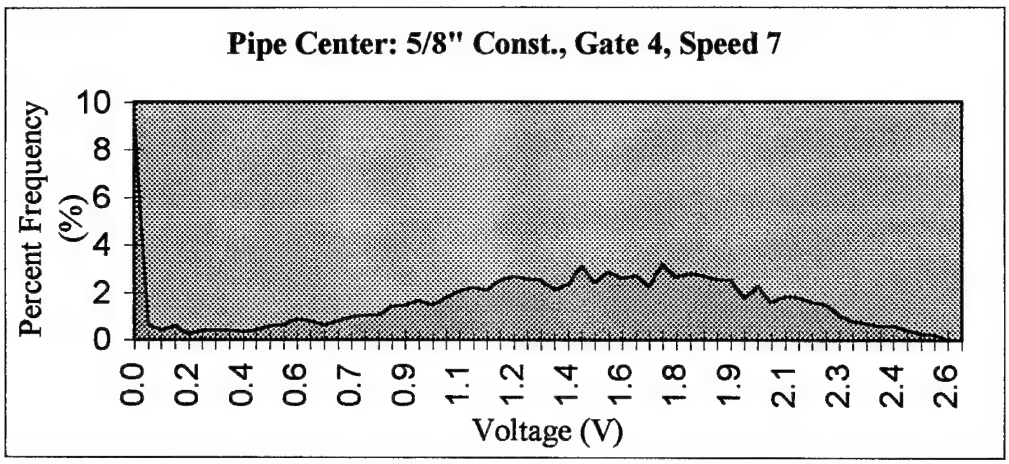


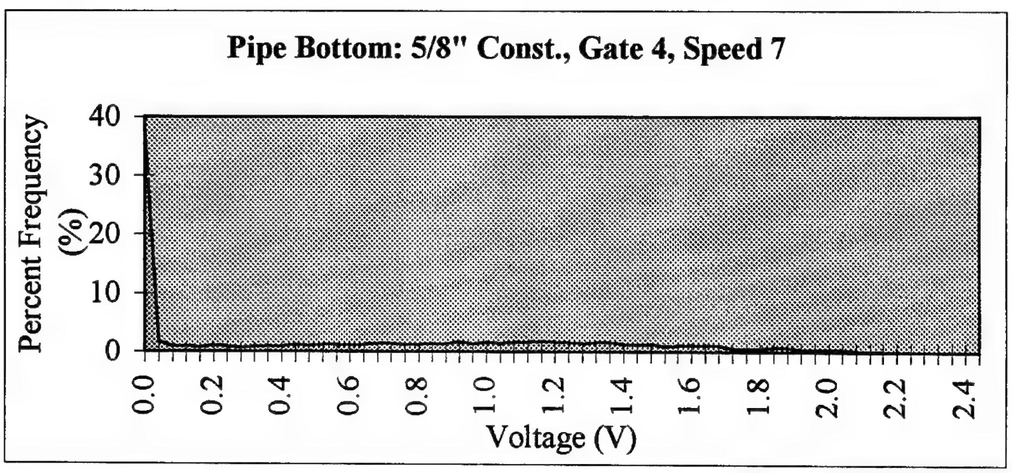


Cellulose Mass Fraction ≈ 40%

APPENDIX E-4: Mixture Dispersion Laser Test Histograms

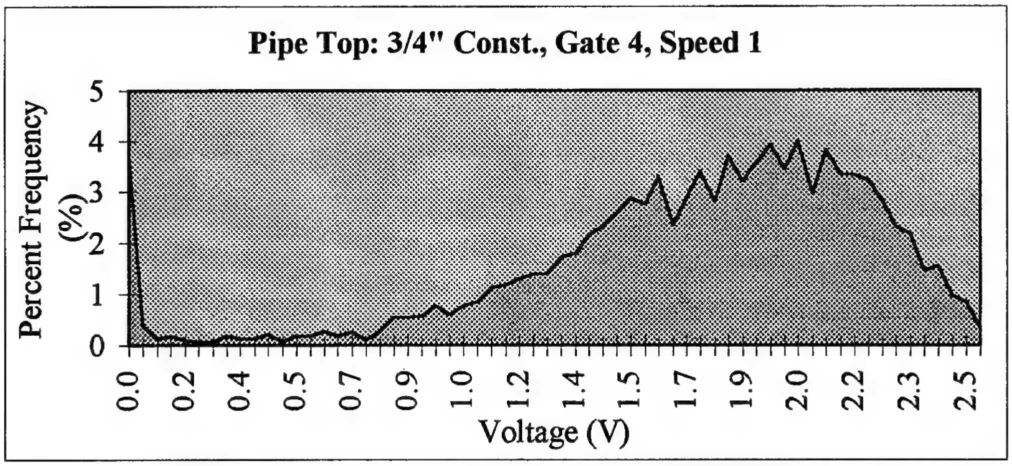


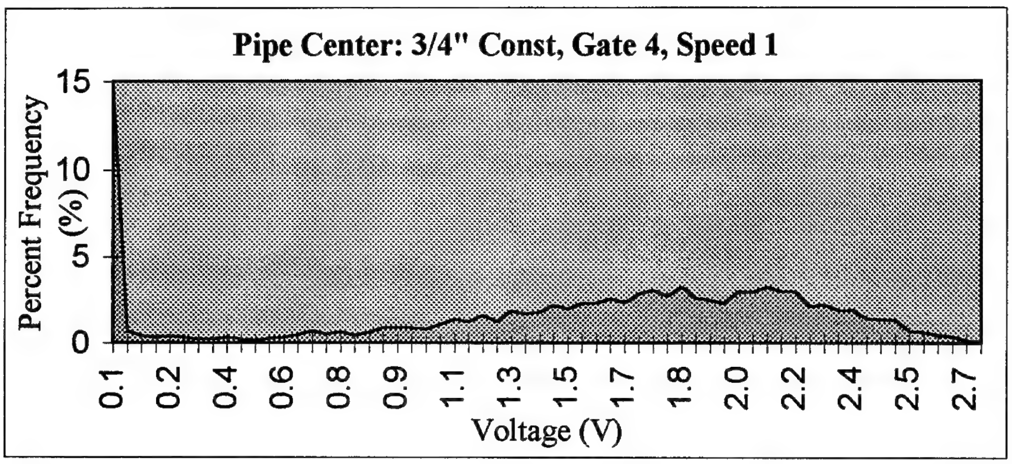


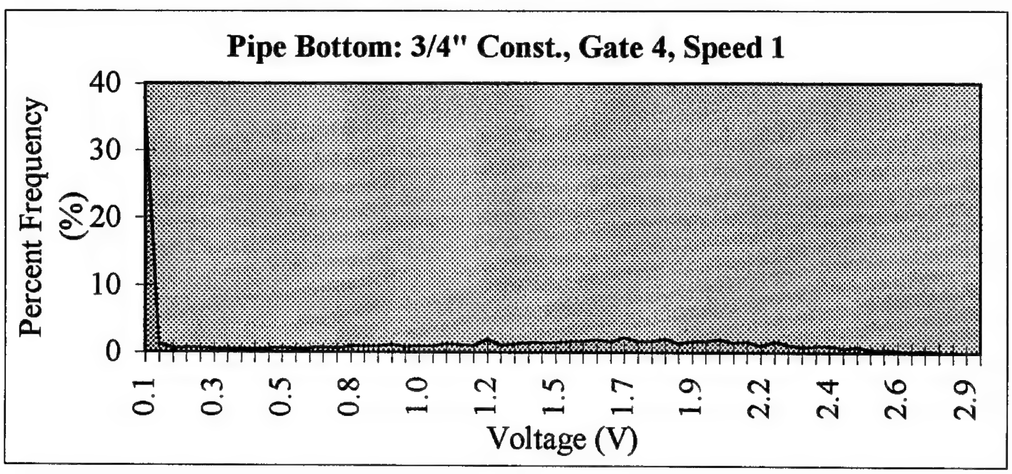


Cellulose Mass Fraction ≈ 45%

APPENDIX E-5: Mixture Dispersion Laser Test Histograms

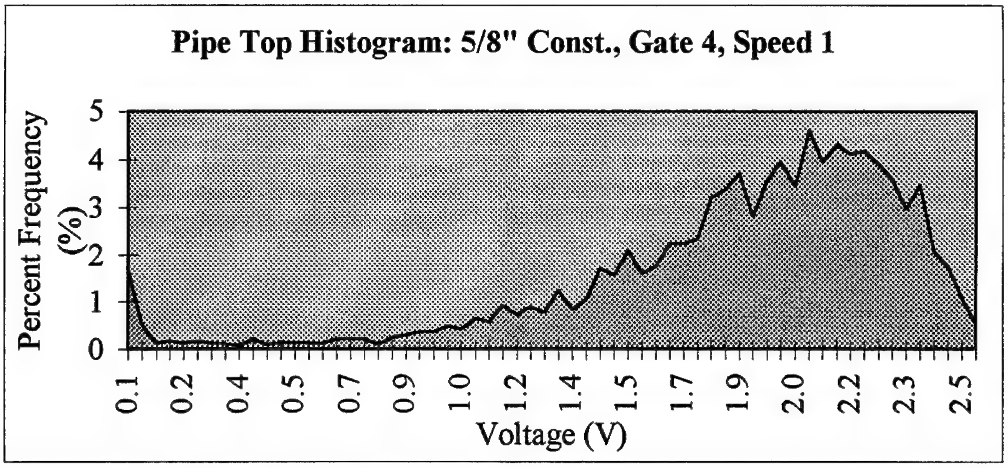


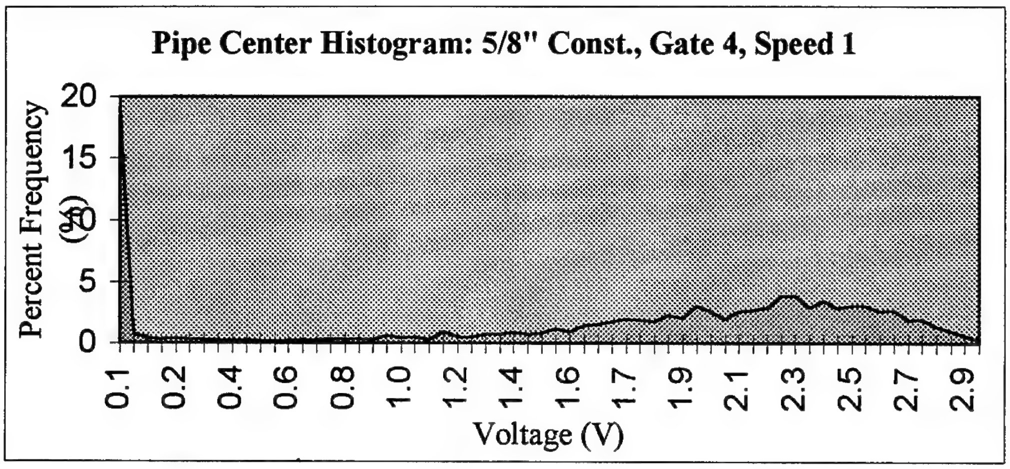


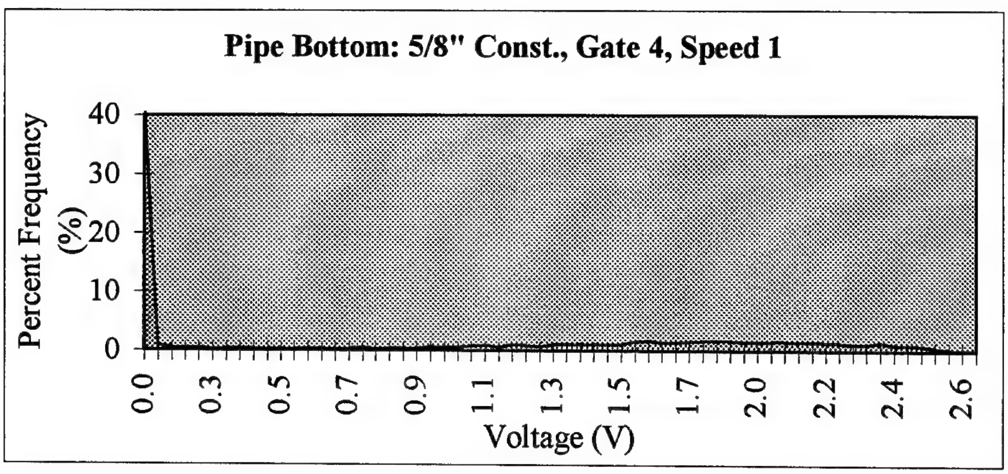


Cellulose Mass Fraction ≈ 53%

APPENDIX E-6: Mixture Dispersion Laser Test Histograms

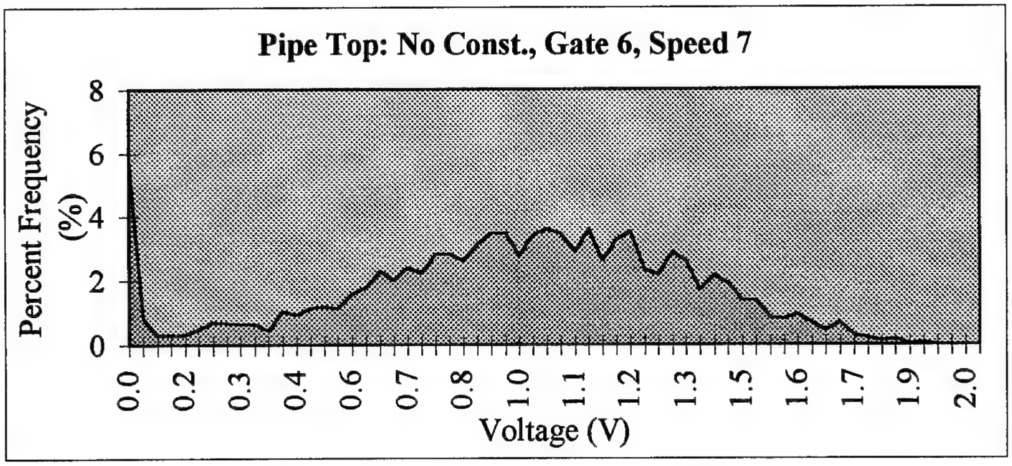


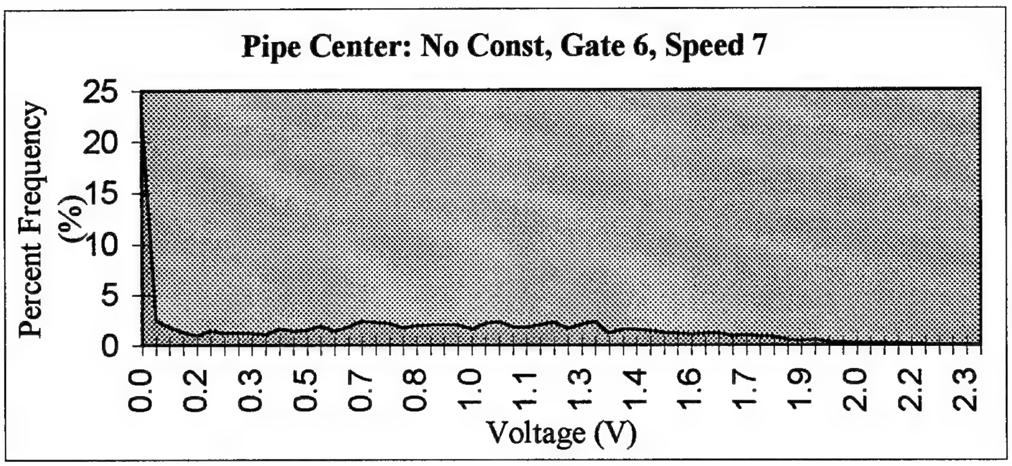


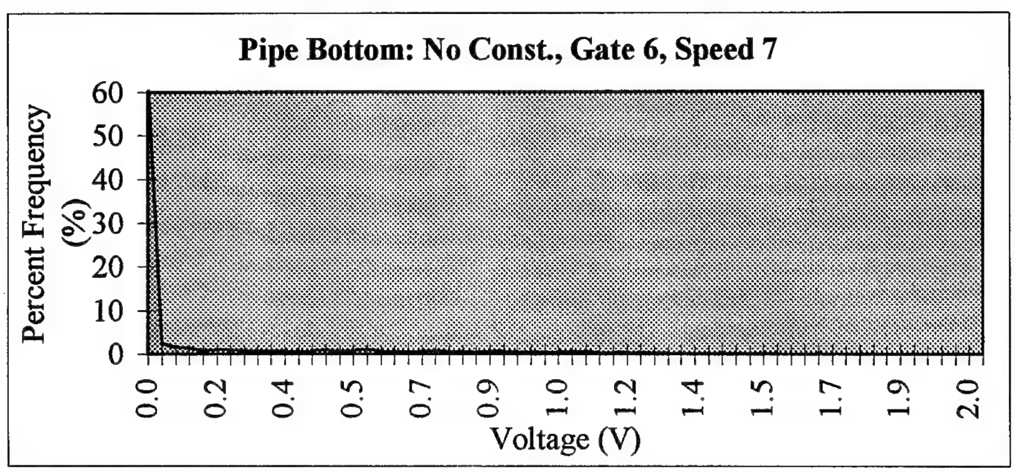


Cellulose Mass Fraction ≈ 56%

APPENDIX E-7: Mixture Dispersion Laser Test Histograms

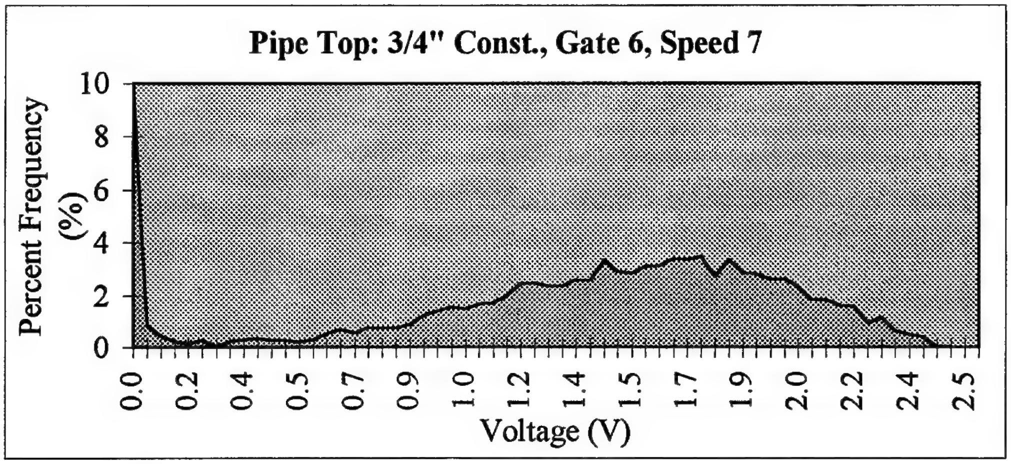


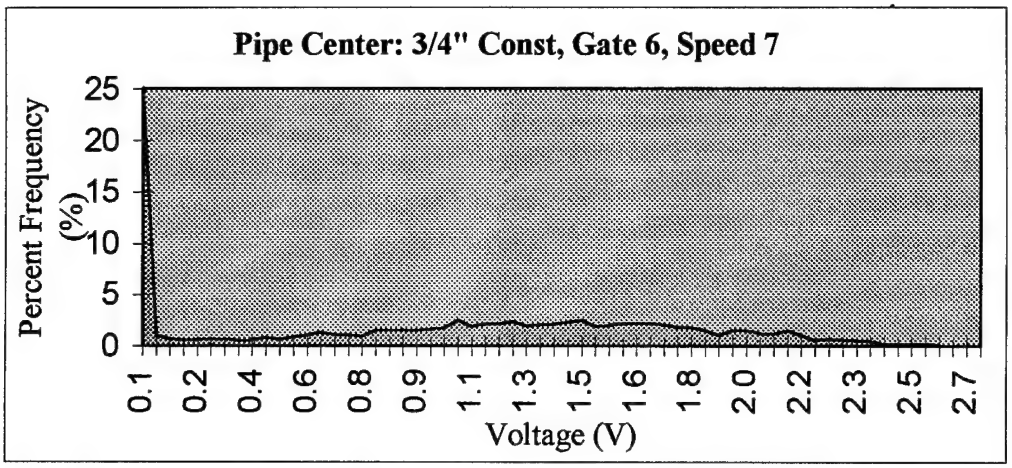


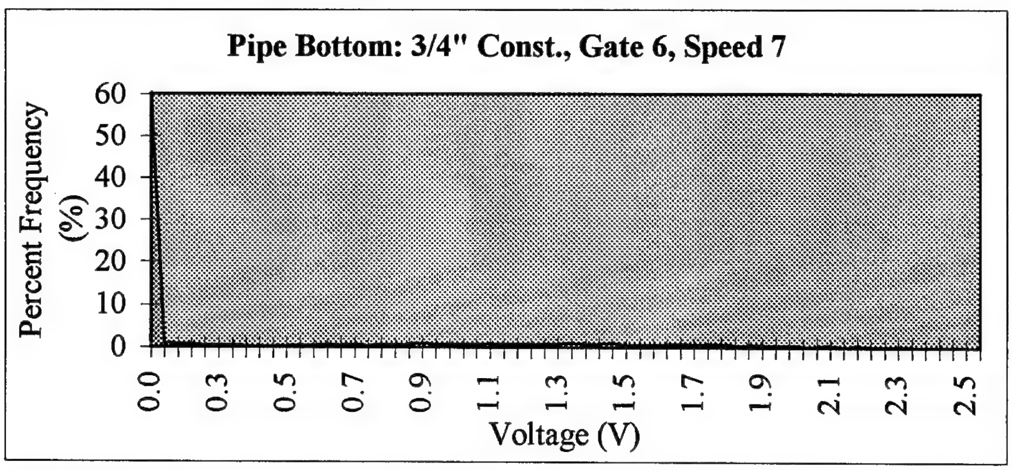


Cellulose Mass Fraction ≈ 58%

APPENDIX E-8: Mixture Dispersion Laser Test Histograms

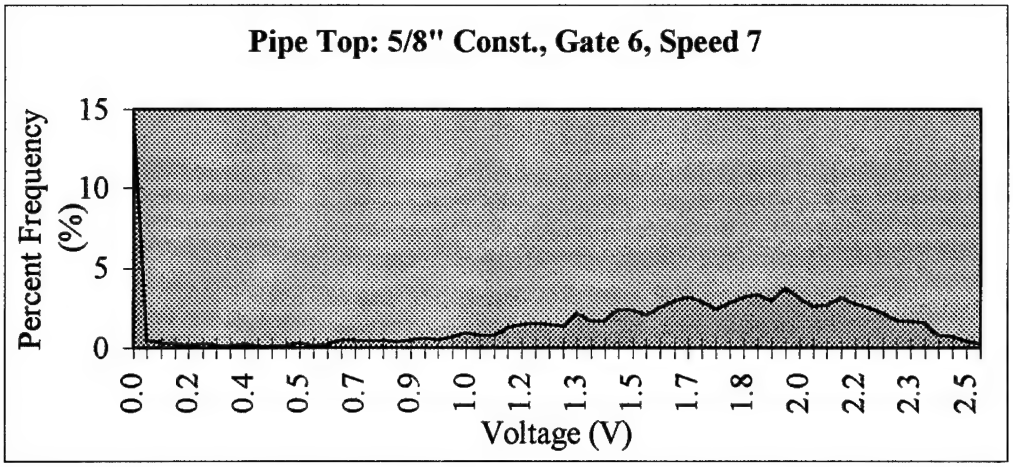


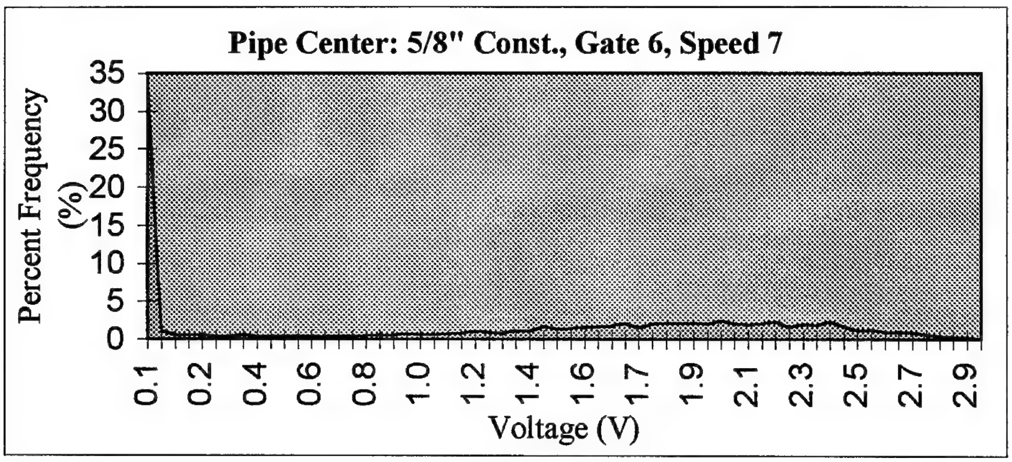


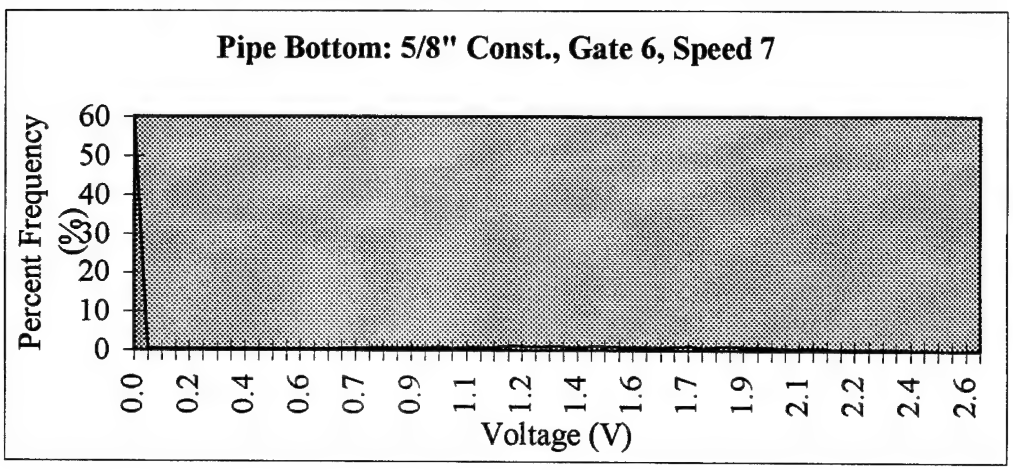


Cellulose Mass Fraction ≈ 67%

APPENDIX E-9: Mixture Dispersion Laser Test Histograms

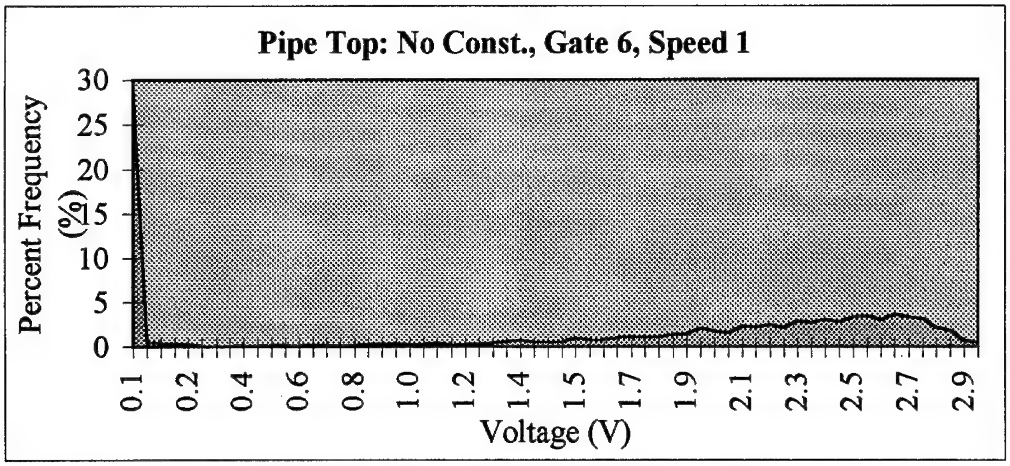


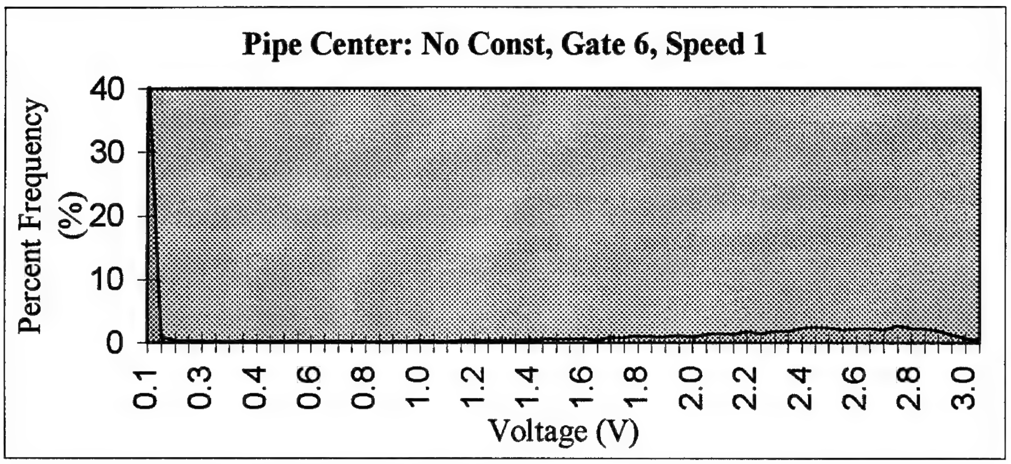


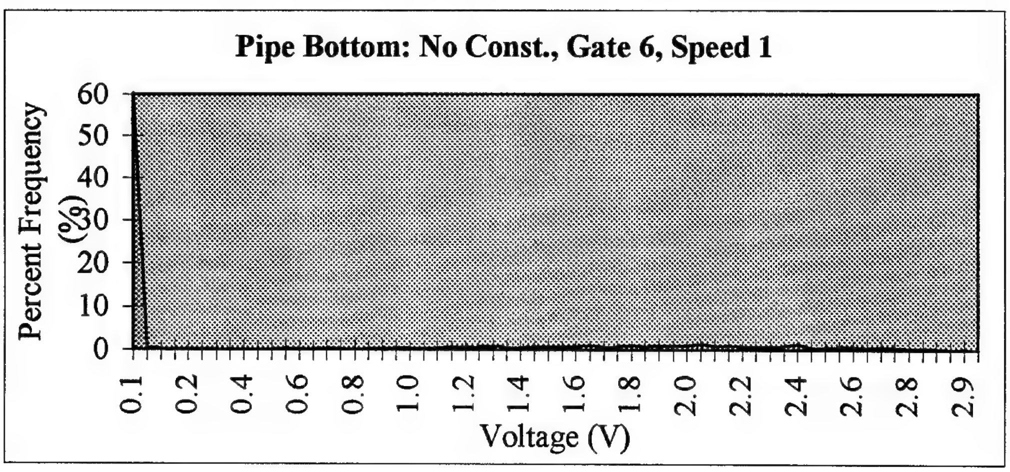


Cellulose Mass Fraction ≈ 69%

APPENDIX E-10: Mixture Dispersion Laser Test Histograms

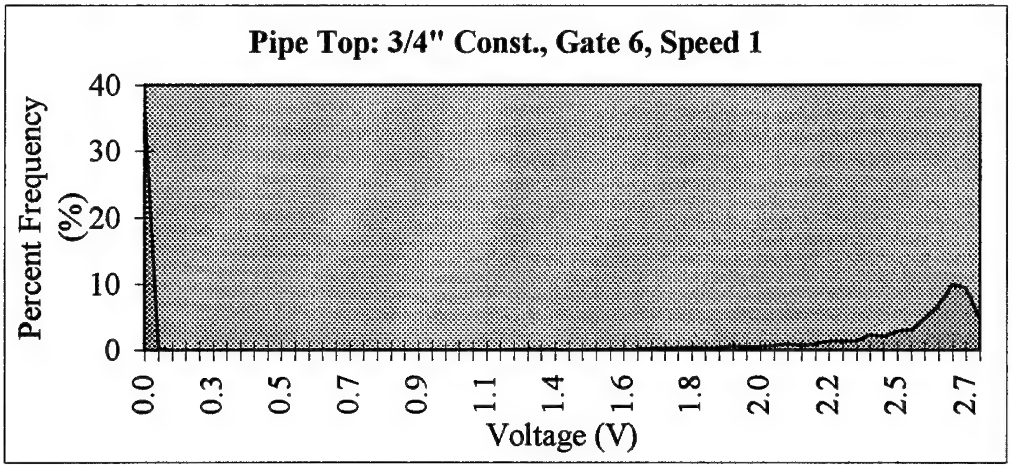


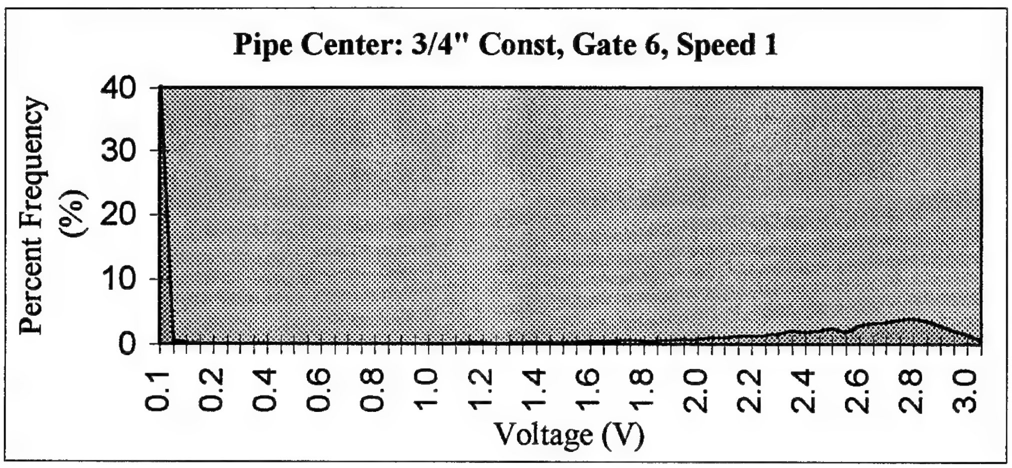


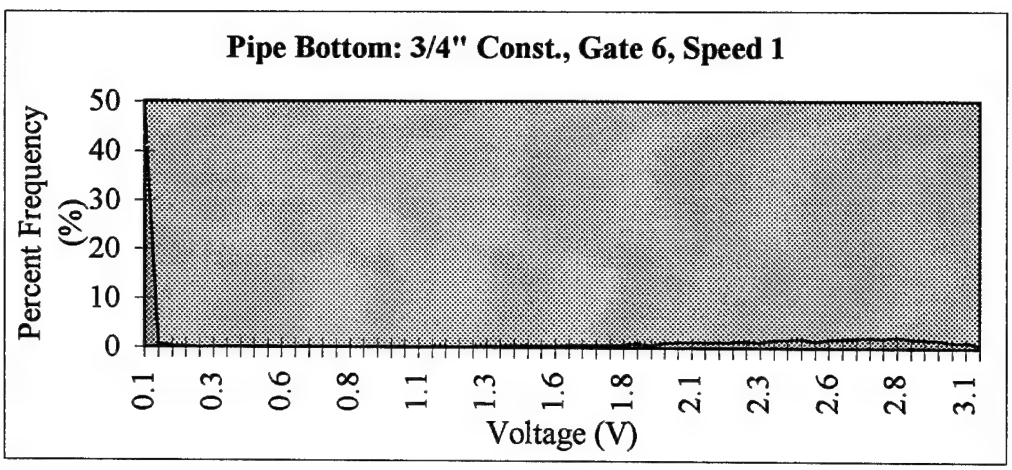


Cellulose Mass Fraction ≈ 72%

APPENDIX E-11: Mixture Dispersion Laser Test Histograms

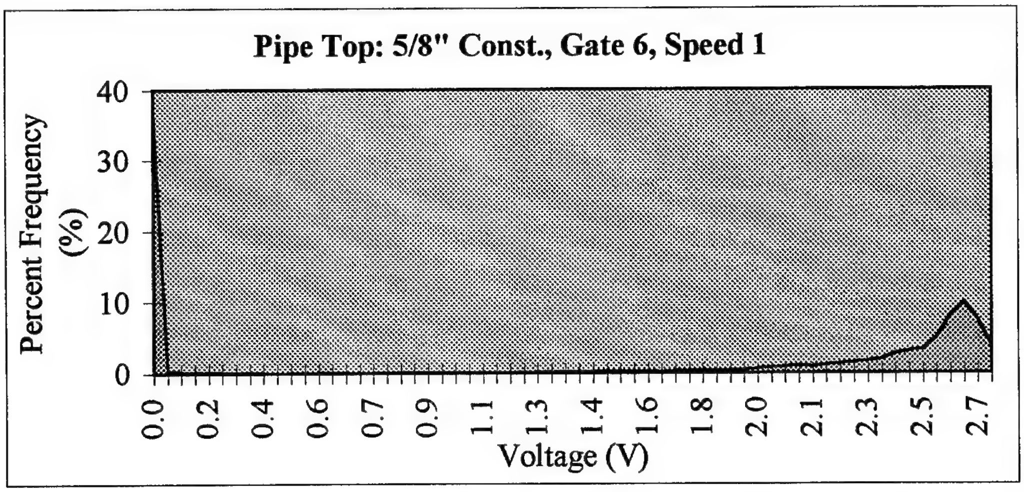


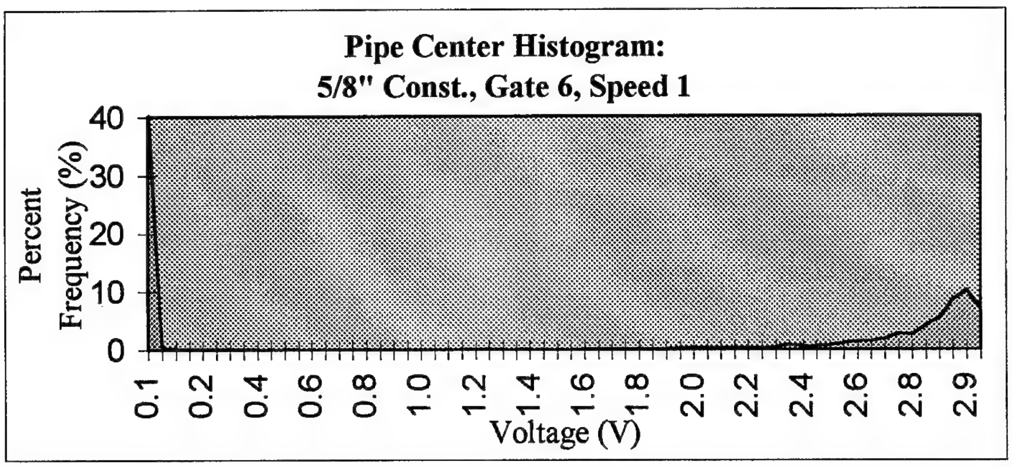


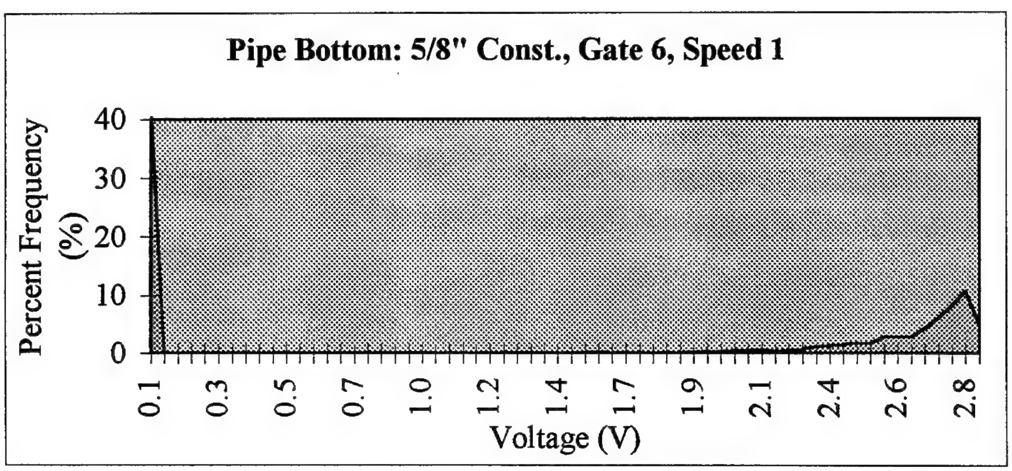


Cellulose Mass Fraction ≈ 77%

APPENDIX E-12: Mixture Dispersion Laser Test Histograms

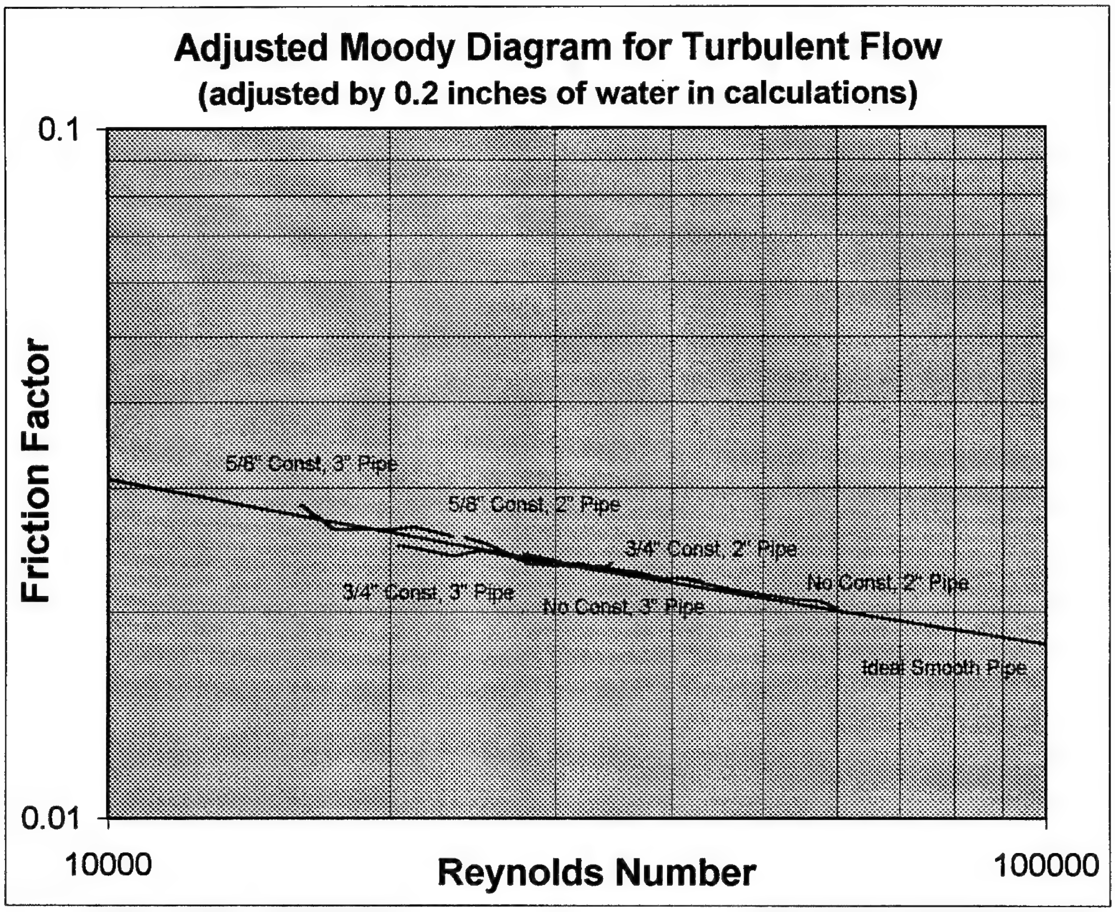






Cellulose Mass Fraction ≈ 80%

APPENDIX F: Adjusted Air Flow Moody Diagram



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ABSTRACT

Title of Thesis: CREATIVE DESIGN METHODS AND INVESTIGATION OF CELLULOSE FIBER TRANSPORT AND APPLICATION SYSTEM

Degree Candidate: Mack-Jan Honoré Spencer

Degree and Year: Master of Science, 1998

Thesis directed by: Professor Kenneth Kiger
Professor Linda Schmidt
Department of Mechanical Engineering

Many difficult design problems require the development of creative design solutions to achieve feasible results. Designers and engineers have searched for methods to enhance creativity in problem-solving to acquire new ideas. A creative design method is a process by which new, independent ideas are generated using knowledge to solve some problem or achieve an objective. Four prominent creative design methods were investigated to explore the extent to which they actually enable creativity by applying them to the design of a novel cellulose application system. Correlations between the four design methods were also discovered. These investigated methods were analogical reasoning, brainstorming, synectics, and the theory of inventive problem solving (TIPS).

In support of the cellulose application system design, a scientific investigation examining the pneumatic suspension and transport of cellulose fibers was conducted. Measurements of air pressure gradients were conducted for various cellulose mass fractions to investigate the pressure drops involved in air-cellulose flow in pipes. Additionally, mixture dispersions were examined using laser testing to analyze the physical properties of air-cellulose mixtures in transport. Moody diagrams and pressure gradient curves were developed and compared to the physical dispersion characteristics of the air-cellulose mixtures.

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